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Front Cover: View of waves striking the west end of Martinique Beach as Post-tropical Storm Noel wanes late on November 4, 2007. Earlier in day waves had flooded the beach and transported rocks across the dunes onto an access road. ***Photo PB040302, R. Taylor***

ABSTRACT

Observations of coastal infrastructure and detailed surveys of physical changes at eight beaches document the impacts of Post-tropical Storm Noel that struck the Atlantic coast of Nova Scotia on November 3-4, 2007. The surveys were part of an ongoing investigation of the impacts of major storms on different shore types and their rate of recovery. In addition, flood water levels and wave run-up extent were documented to better define shores vulnerable to these coastal hazards.

The area of gale to storm force southerly to southwesterly winds in Noel extended along most of the Atlantic coast of Nova Scotia. Waves in excess of 8 m height lasted nearly 6 hours, with a focused direction of 190-220 degrees as they peaked in height. Wave set-up increased water level but it was still about 50 cm less than maximum levels reached during Hurricane Juan. If Noel had occurred a week earlier during spring tides, the damage probably would have been significantly greater in area, and possibly in intensity.

Power outages and minor damage from waves tossing debris and rocks across adjacent roads and properties occurred in similar locations as past storms. No official dollar values have been published for the cost of Noel. The worst damage to infrastructure was on the outer coast, in the vicinity of the Lahave River, at Peggy's Cove and scattered locations along St. Margarets Bay.

Waves overwashed all shores less than 4.4 m elevation. Backshore dunes were flooded a maximum distance of 84 m from the beach. A low gravel barrier beach crest was pushed nearly 6 m landward and its lagoon shore was extended 10 m. Where backshores were higher, wave run-up extended to elevations of 6 m across vegetated sand dunes and possibly as high as 12 m across bedrock shores. Flood waters reached 1.9 to 2.3 m elevation at lagoons and estuaries along the Eastern Shore and possibly as high as 3.1 m along the South Shore.

Most of the beaches still retained their maximum sediment build-up when Noel struck which lessened the wave impacts. Natural dunes were cut back less than 7 m, except where water was funneled through existing dune cuts used as trails, or water turbulence was intensified around artificial structures, such as boardwalks and fences. Channels were cut through weak parts of dunes at Lawrencetown, Martinique and Cherry Hill beaches. A backshore pond along Hartling Bay was completely drained and became tidal when the barrier beach fronting it was breached.

The Atlantic coast of Nova Scotia has been retreating landward for thousands of years because of sea level rise. Storms such as Noel cause one small step in that process which varies in intensity depending on the condition of specific shores. For the eight beaches investigated Cherry Hill and Cow Bay continue to rapidly evolve, parts of Lawrencetown and Martinique beaches are now more susceptible to rapid change, Hirtles and Miseners-Long beaches continue to slowly migrate, Conrads Beach is in a phase of building and less impacted, and natural movement of Crescent Beach became more constrained with the addition of rock in response to dune erosion caused by Noel.

Table of Contents Page

Table of Contents Page

Introduction

The Atlantic coast of Nova Scotia is vulnerable to many large storms that track up the eastern seaboard of North America. Therefore it is a prime location to monitor the effects of storms on shoreline stability. Barrier beaches are vulnerable to significant change when they are struck by storms with high water levels and /or a longer duration of large waves. In the past, efforts focused on examining the impacts of major storms and the rate of barrier beach recovery from these events. Repetitive surveys before and after storms were completed at a network of shoreline monitoring sites established by the Geological Survey of Canada (Taylor et al. 1997a, b, 2004). Immediately after post -tropical storm Noel, visual observations by the authors and reports in the media indicated that many of the same shores impacted in the past were also impacted by Noel. Therefore, following the same procedures used in the past, many of the same beaches were resurveyed after "Noel". Objectives were to document the magnitude and type of physical shoreline change, the extent of wave run-up and flooding and to compare the impacts with those from previous storms. The information will contribute to a broader understanding of expected changes to shorelines in Nova Scotia as a result of increased storminess.

Climatic and Oceanographic Processes

A summary statement about Post-tropical Storm Noel was issued by the Canadian Hurricane centre (*http://www.atl.ec.gc.ca/weather/hurricane/index_e.html.)* The statement describes the development and northward movement of Noel along eastern North America and its spread into Atlantic Canada.

Wind speeds and rainfall at a number of locations in Atlantic Canada were also provided in the summary. For example Noel produced wind gusts reaching 180 km/hr at Wreckhouse and 113 km/hr at Port aux Basques in southwest Newfoundland, 135 km/hr at McNabs Island, Halifax Harbour, NS; 111 km/hr at North Point and East Point, PEI. and 87 km /hr at Miscou Island, NB (Table 1). Large amounts of rainfall also occurred. The heaviest rainfall was unofficially reported as 130 mm at Smelt Brook, Cape Breton Highlands, NS and 112 mm in central New Brunswick.

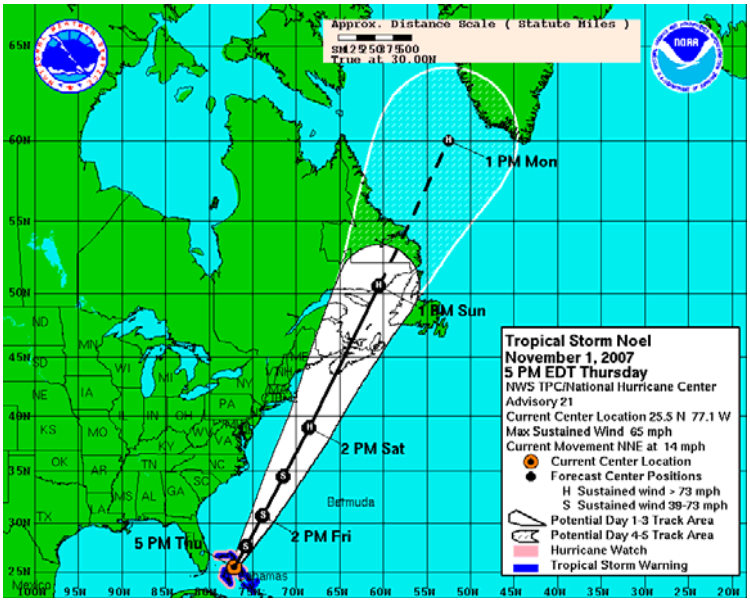


Figure 1. Predicted track of Noel on Nov. 1, 2007 issued by National Hurricane Center and NOAA.

The area of gale to storm force southerly and southwesterly winds was at least an order of magnitude larger in Noel than Hurricane Juan in 2003, and extended along most of the Atlantic coast of Nova Scotia. Sustained wind speeds offshore peaked at 70 knots (130 km/hr) during Noel and 82 knots (152 km/hr) during Juan. Winds switched from southeast to southwest and west in Yarmouth around 03:00 AST and shifted more gradually from southeast to southwest farther east along the Atlantic Coast of NS. At the mouth of Halifax Harbour winds blew from the south just after high tide and from the southwest by 07:00 AST.

The larger area of strong winds during Noel produced waves at least as intense as for Juan, and covered a much larger area of the coast. The highest significant wave height of 13.9 m was reported at the Georges Bank buoy. Significant wave heights recorded at buoy 44258, just south of Halifax Harbour, exceeded 8 m for 6 hours, from 00:20 to 06:20 AST, and reached a maximum significant wave height of 10.3 m and a 14.2 second peak period at 05:00 AST, just after high tide (Fig.2, 3). Environment Canada re-examined the spectral and other data from the buoy, determining that the 10.3 m measurement should have been 11.0 m, and the peak period should have been near 17 seconds. Also, just after this observation the wave field intensified enough to drag the buoy and its anchor about 100 metres to the northeast for over 2 hours, making the validity of wave measurements during this period untrustworthy. However, given that 11 metre waves weren't enough to move the buoy, the actual relocation of the buoy provides strong evidence that wave intensity increased significantly above 11 metres during this period.

When compared to Juan, Noel produced a greater wave field intensity, extended duration and geographic area covered. During Juan the largest waves didn't extend much west of Mahone Bay; during Noel they extended significantly farther west. Navigational buoys as far as the Bay of Fundy were displaced by the waves. Also, given that Juan made landfall near Prospect, the waves left of storm track were primarily swell with admittedly long periods (a new estimate for waves during Juan is near 16 seconds period with a 400 m wavelength, and for Noel 17+ seconds with a 450 + m wavelength). In addition the longer period waves of Noel would have interacted with the seabed at greater depths.

Water levels of 2.4 m, CD (dockyard) and 2.5 m CD (BIO) were reported in Halifax as a storm surge of 0.75 m and 0.90 m respectively coincided with high tide, just before 04:00 hrs AST on November 4, 2007 (Fig. 3). In Yarmouth the maximum surge of 0.65 m coincided with the following low tide producing a water level of 4.6 m CD (Table 1). The storm surge included a significant wave setup component.

The operational storm surge model of Environment Canada predicted a surge of near 40-55 cm for most areas along the Atlantic coast of Nova Scotia which was less than the surges that actually occurred. However, the model does not include the effects of wave set up which could account for the difference between predicted and actual water levels which was 30-50 cm. If this event had occurred in the previous week when spring tides were 40-50 cm higher, in all probability the intensity of coastal damage would have been

comparable to Juan, and would have extended over much of the Atlantic Coast of Nova Scotia

Wave and tidal forces nearly peaked together when the storm stuck the Atlantic coast of Nova Scotia. Ryan Mulligan of Dalhousie University (pers. com., 2007) observed very strong wave-driven longshore currents less than 500 m from shore, in water depths of less than 10m, in Lunenburg Bay. He believes similar currents could have been generated elsewhere along the coast and may be responsible for the large volumes of beach sediment moved during the storm.

A number of local residents interviewed the next day at various beaches commented that everything seemed fine until the winds shifted to the southwest, as the storm passed around 04:00 hrs (Table 1). It was the same time (04:04 hrs Nov 4) that very strong winds were felt in downtown Dartmouth

Figure 2. Example of breaking waves generated by Post-tropical Storm Noel at Peggy's Cove, NS on Nov. 4, 2007 (unknown photographer).

Public Discussions

CBC radio kept an all-night vigil with a phone-in show that enabled people from all over the Maritimes to report local weather conditions and any impacts they experienced. A sampling of the reports included:

- 150,000 customers without power in NS (most between Bridgewater and Sheet Harbour, and 77,000 in New Brunswick, local outages occurred in PEI, such as in Summerside.

- Football-size rocks thrown across the road by Queensland Beach - the road was buckled as if an earthquake had struck. A number of other shore roads were briefly closed because of rocks and debris including Tangier, Cow Bay, Lawrencetown, Three Fathom Harbour, Crescent Beach, Green Bay and West Dublin in Lunenburg County. Near West Berlin, Queens County a shed was floated to the edge of the highway and a highway bridge was closed after being severely damaged.

- The Confederation Bridge to PEI was closed to high-sided vehicles and it felt like you were driving through a wind tunnel said one person who had crossed the bridge in their car

- no flooding was reported from New Brunswick coastal areas as the surges did not coincide with a high tide and less impacts were felt along SW Nova Scotia than originally anticipated

- Building damages were reported in a number of places including a trailer roof in Dartmouth, and an elevator shaft at a seniors complex in Sydney.

Additional interviews with persons living in coastal areas potentially impacted by Noel were made on the Sunday afternoon, Nov. 4. The information collected is summarized in Appendix 1.

Table1. Selected weather and sea level conditions reported in Atlantic Canada during Post- tropical Storm Noel. Data derived from National Climate Data and Information Archives (EC) and Tide Gauge Records (DFO). Maximum sea levels include the surge component. Times are listed as local standard time (LSD)

Station	Date	Local Time	Max. Sea level (chart datum)	Surge	Max Recorded Surge	Winds (hourly)		Lowest Station Pressure and Time
	(2007)	(LST)	(m)	(m)	(m) (Time)	Speed (km/hr) (Time LST)	Direction (°)	(kPa)
Yarmouth, NS	3 Nov.	17:45	4.55	0.46	0.67 (23:15)	56 (06: 00 & 08:00)	280	96.59 (02:00)
Saint John, NB	3 Nov.	19:00	7.34	0.26	0.51 (23:15)	48 (19:00)	70	96.04 (04:00)
McNabs Is / Halifax, NS	4 Nov.	03:45	2.37	0.79	0.79 (03:45)	113 (04:00)	170	97.35 (04:00 & 05:00)
North Sydney/ Sydney, NS	4 Nov.	04:00	1.17	0.02	0.37 (18:00) Nov 5	67 (08:00)	190	98.06 (07:00)
Shediac / Moncton NB	4 Nov.	00:30	1.9	0.74	0.74 (00:30)	67 (08:00)	240	96.24 (06:00)
Charlottetown, PEI	4 Nov.	20:00	2.67	0.37	0.70 (13:30) Nov.5	67 (07:00)	180	96.63 (07:00)
Wreckhouse, NL	4 Nov.	-------	-------	------	---------	107 (08:30)	130	98.23 (08:30)

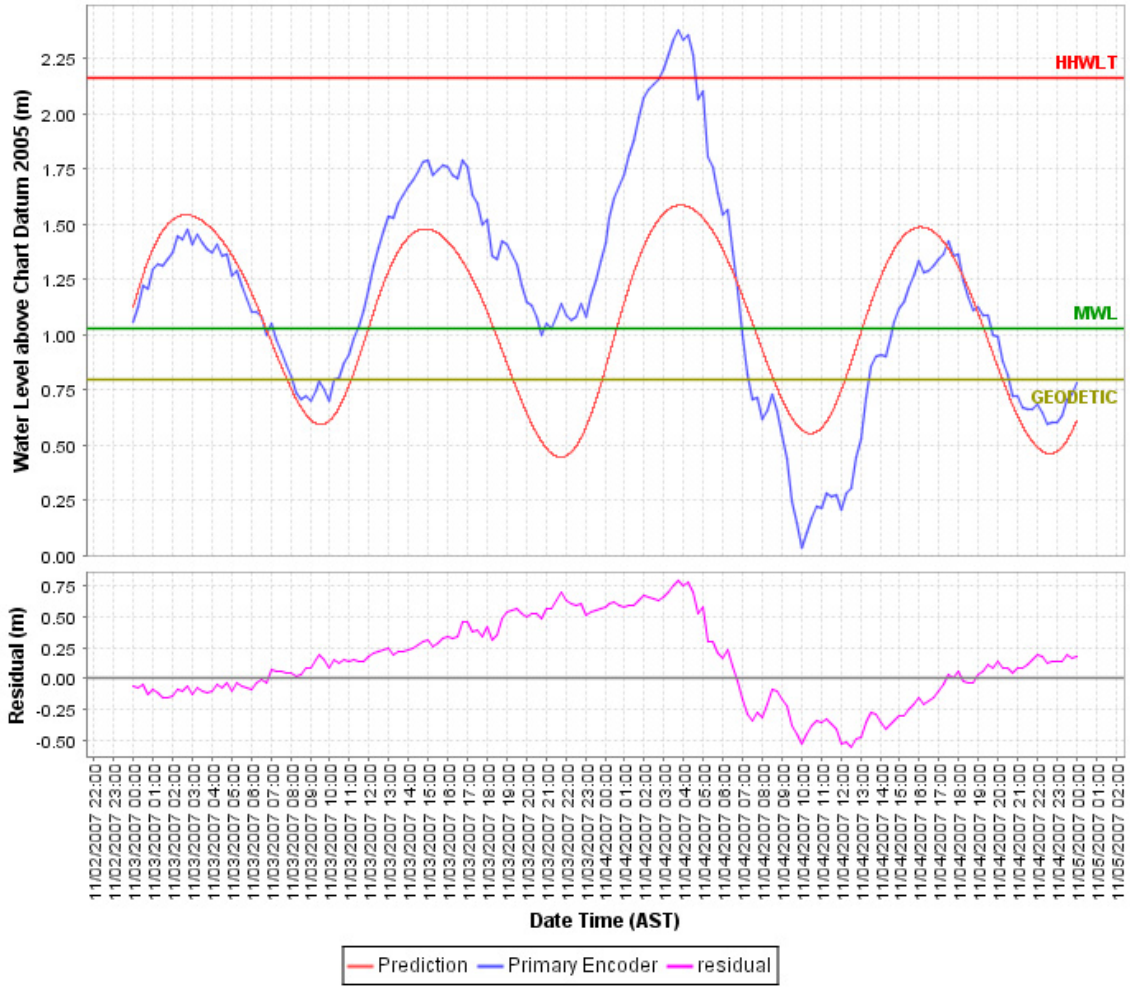


Figure 3. Halifax tide gauge record from November 2 to 6 showing the surge developed during Noel on Nov. 4. The peak surge coincided with high tide around 04:00 (AST) producing a total water level of 2.37 m above chart datum. Total water level during Hurricane Juan in 2003 was 2.9 m in Halifax (Chart courtesy of Canadian Hydrographic Service).

Figure 4a. Examples of wave impacts from Noel to coastal infrastructure along the Atlantic coast of Nova Scotia (a) rock debris and damage to pavement Cow Bay Road; (b) bent guard rail and debris, Eastern Passage Shore Road; (c) flooding at Wyndenfog Lane, Lawrencetown Beach (Betty, Houghton); (d) damage to wharves and sailboats Halifax Harbour; (e) floating structures, West Berlin, N.S. (Kirsty Toussignant); and (f) downed power lines Crescent Beach Lunenburg Co. (Bridgewater News). All photos were taken on November 4, 2007 by R. Taylor (GSCA) unless noted.

Field Observations

Visual observations of the impacts of Noel were collected from a variety of coastal locations by the authors within the first week after the storm. Each person focused on areas they were most familiar with and had visited following Hurricane Juan. Detailed surveys of beach changes were completed at eight beaches along the Atlantic coast of Nova Scotia between November 5 and 23, 2007. A summary of the results of those surveys at each beach is presented next.

Impacts to Infrastructure:

Immediately after Noel struck and for the next few weeks, the authors and in particular D. Mercer visited the same parts they had visited after Hurricane Juan to compare the impacts of the two storms. Detailed comments and locations impacted are listed in Appendix 2, 3. In this section we summarize the impacts of Noel on coastal infrastructure (Fig. 4).

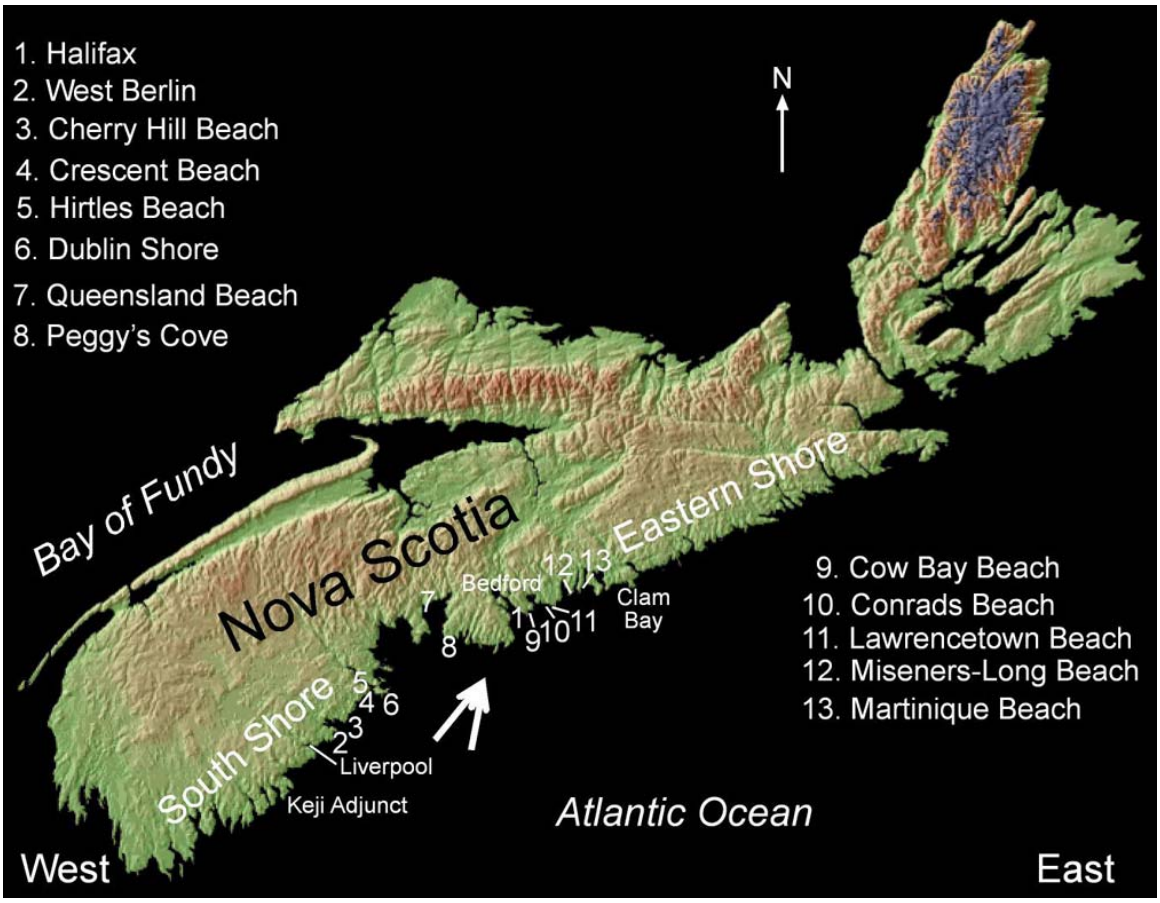


Figure 5. Coastal locations where the impacts of Post-tropical Storm Noel were observed and measured in November 2007. White arrows indicate direction of largest waves.

East of Halifax Harbour to just east of Clam Bay, flooding was common across many of the low-lying shore roads including: Story Head, Chezzetcook Inlet, Fishermens Reserve, Three Fathom Harbour, Lawrencetown and Conrads Beach roads, Cole Harbour and Cow Bay. In many of the same areas sand, pebble, rock or tree debris covered parts of the roads limiting vehicle access for hours to a day. At Three Fathom Harbour one witness reported a 0.6 m depth of water was flowing over the road and at Lawrencetown Beach road a driver had abandoned his car when it was engulfed by waves overwashing the dunes ~ 05:00 AST, Nov. 4.

Within Halifax Harbour, flooding and debris lines were observed at a number of places, there was minor damage to marinas, and one vessel was washed onshore near the Sackville River mouth. Damage to signs and houses and isolated tree falls occurred throughout the area, but overall the impacts were less severe than during Juan because the wind stress was lower.

West of Halifax Harbour to Liverpool, impacts from Noel included damage to wharves, debris on property and roads, displaced sheds, marine navigational aids and boulders, and short term flooding of roads. The most disruptive and costly impacts from waves were observed at West Berlin, Dublin Shore, Crescent Beach, Queensland and Peggy's Cove. At West Berlin a highway bridge was damaged and closed, homes under construction were flooded, a large shed was floated to the highway (Fig. 4e) and the road at Ragged Harbour was blocked as the beach was pushed landward across it. At Dublin Shore the government wharf was badly twisted, many fishing sheds were damaged and the access road was eroded. Crescent Beach provides an access road and power transmission lines to the residents of the LaHave Islands. The power poles in the dunes were undermined and had to be replaced and the road had to be cleared of sand and wood debris in several locations. Following the storm, more than 10,000 tons of armour rock was added to the front of the dunes to protect the road. Queensland Beach, which is vulnerable to most storms with the right orientation was particularly hit hard by Noel. The beach and parking lot became a boulder field; the road at the eastern end near Route 3 was badly heaved and eroded on the ocean side and part of Route 3 was eroded, disrupting traffic flow for several days.

Residents of Peggy's Cove described Noel as the worst weather event in living memory. The force of the storm during the night was well illustrated by a couple of storm chasers on websites http://www.stormchaser.ca/Noel/Noel.html and http://www.ultimatechase.com/Hurricane_Video.htm. Breaking waves were reported on Youtube as 120 ft and broke a south-facing window in the lighthouse. Water flowed across the northeast corner of the parking lot, estimated to be 12 m above sea level. Waves remained very large a day after the event (Fig. 2). Rocks as large as 6m x 5m x 2m were moved, including rocks tossed onto the Sou'wester Restaurant parking lot and against the sewage treatment plant. Water flowed through bedrock gullies scouring terrain and flipping sods adjacent to the restaurant and parking lot. Doug Mercer provides a more complete list of impacts within the village (Appendix 3). The most remarkable story is the flooding of the village by seawater that came from the east. Above the village there is a shallow east-west valley that drains west into the harbour and east to the ocean.

At the highest point of the valley there is a breakwater/dam which has existed since 1915 and has never been breached, even during Hurricane Juan (Appendix 3). It was built to prevent seawater from flooding the village. After hours of steady pounding by water during Noel, the breakwater broke about 03:00 am. Water flowed into the village eroding both sides of the harbour road and carrying sediment and other debris into the harbour as it flowed past and through a number of buildings including a gift shop named Beal's Bailiwick.

Impacts to Beaches

Cow Bay Beach, Halifax County

Cow Bay Beach is a 1 km long barrier beach fronting Cow Bay Lake just east of Dartmouth. It is low gravel barrier which is easily overwashed during storms. From 1954 to1992 the central beach, between channel A and line L3a (Fig. 6), was narrowed from 121 m to 30 m. Between 1991and 2000 the barrier beach crest migrated by 20 m, or a mean rate of 1.8 m/a. Cross-shore lines (L), marked L1, L3a, and the beach crest east of line 3a were resurveyed on Nov. 23, 2007 to document the impacts of Noel.

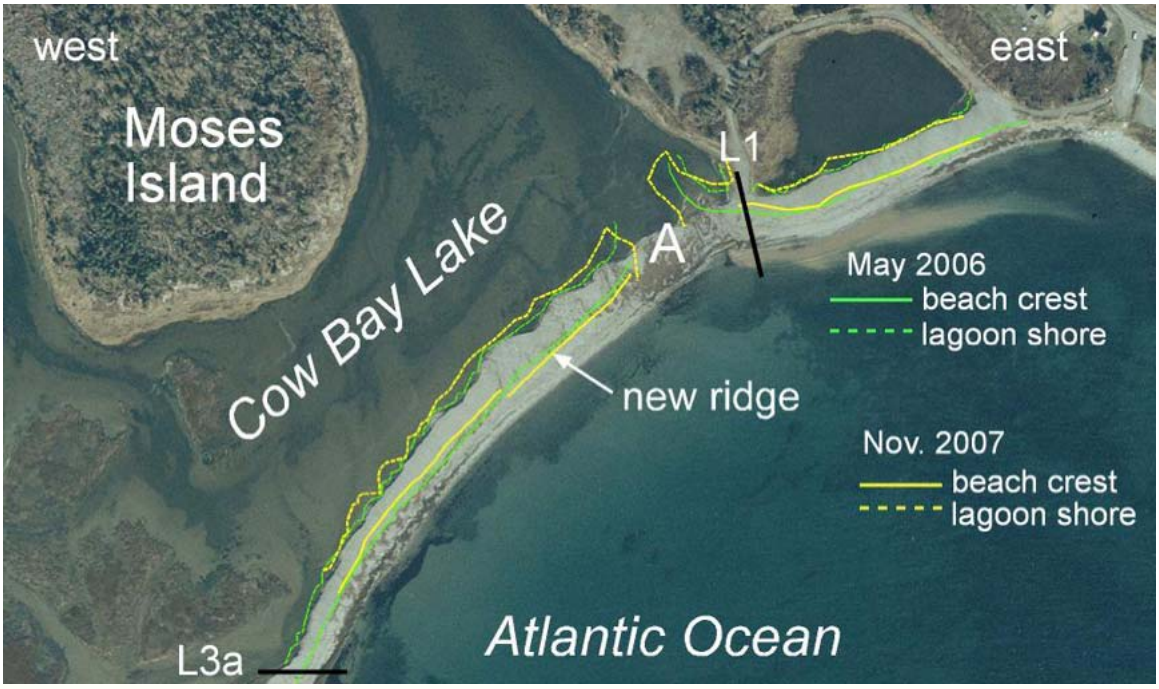


Figure 6. Location of cross-shore survey lines (L) used to document the physical changes across Cow Bay Beach. Plan maps of Cow Bay Beach crest and lagoon shoreline in May 2006 and after Noel in November 2007 are superimposed on the 2003 air photo. The lagoon shoreline was extended landward an average of 8 m and a maximum of 11 m by waves washing over the beach during Noel (Digital 2003 air photo 4460634, courtesy NS Department of Natural Resources.

In 2006 the average elevation of the beach crest was 3.0 m and increased to 3.9 m near line L3a and at the east end of the beach. By early morning November 4, 2007 waves from Noel had flattened the central barrier beach and were freely flowing into Cow Bay Lake through two channels (breaches) A and B cut through the beach (Fig 6, 7). The average beach crest elevation was reduced to 2.5 m and the previous highest areas were lowered to 3.7 m (Fig. 7c). The central barrier crest was lowered to similar levels (1.9 to 2.6 m) observed after Hurricane Juan. Along the eastern beach section a washover channel was cut 0.6 m into the beach and extended into the backshore pond. Channel A (Fig. 7c) was widened slightly toward the east but was not cut deeper than its 2006 base level. East of line 3a waves had pushed the barrier crest an average of 5.2 m and a maximum of 6.6 m landward and overwash deposits extended the lagoon shoreline an average of 8 m landward. By Nov. 23 waves had rebuilt part of the beach crest an average of 5 m seaward of the pre-storm crest position however much of the new crest was composed of seaweed. It is anticipated that the crest will rebuild but it will be farther landward and lower than the crest of 2006 because of the transfer of sediment into Cow Bay Lake by wave overwash. The lagoon shoreline retreated an average of 8 m landward into Cow Bay Lake following Noel and a maximum of 10.9 m between 2006 and 2007. The thickness of washover lobes extending into Cow bay Lake was 1.0 to 1.3 m, therefore the volume of sediment moved into the lagoon between 2006 and 2007 back of the mid -section of Cow Bay Beach was an estimated 1880 m^3.

Storm debris lines elevation from wave run-up during Noel were observed at 2.0 m elevation (CGVD28) all around the back of the eastern pond confirming extensive wave overwash and flooding of the ponds during Noel.

Cross-shore surveys were completed at Lines 1 and 3a which now represent the more stable parts of Cow Bay Beach because of a more resistent substrate of till or road fill at line 1 and the high beach crest at Line L3a. Since 2006 the beach crest at line 1 was pushed landward by 5.8 m and lowered by 0.3 and at line 3a it shifted 1.3 m landward and was lowered by 0.2 m. A washover lobe 0.4 m thick was deposited across the old road bed on line 1.

Little change was observed across the lower beach and nearshore at line 1 because of the existence of a cobble boulder shoal, whereas at Line 3a an estimated 0.5 m thickness of sand was removed.

On November 23, 2007, large volumes of seaweed were accumulating alongshore, particularly at line 3a. The seaweed significantly dissipates the impact of breaking waves and offers temporary protection for the beach against further wave destruction.

The recent increase in beach migration has loosened its substrate and increased its porosity resulting in increased volumes of water flowing through the beach. During the 2007 survey we observed seaward directed flows of water at an elevation of 0.83 m which was just below lake water level on line 3a. The decrease in substrate compaction increases the potential for more rapid landward beach migration in future storms or high

water events. However continued landward beach migration is dependent upon waves rebuilding the crest sufficiently high to be knocked over again. Once beach crest elevations decrease to high tide level the beaches become stranded as waves wash over them.

Figure 7. Views of Cow Bay Beach looking east from cross-shore survey line 3a (flags and person mark the line) (a) May 12, 2006 and (b) Nov. 23, 2007 showing the decrease in the beach crest (dash line) elevation caused by Noel (east of the arrow) and the new crest rebuilding (seaweed pile) by November 23. (c) Longshore profile of the beach crest showing its elevation after Hurricane Hortense (27-Sept-96) (Taylor et al. 1997b), and Hurricane Juan (10-Oct-03) (Taylor et al. 2004), its natural rebuilding by May 2006 and its position after Noel (23-Nov-07). In all three cases the beach was lowered to a similar elevation and was rebuilt. Wave washover channels at A and B have remained tidal channels at mid to high tide since Hurricane Juan.

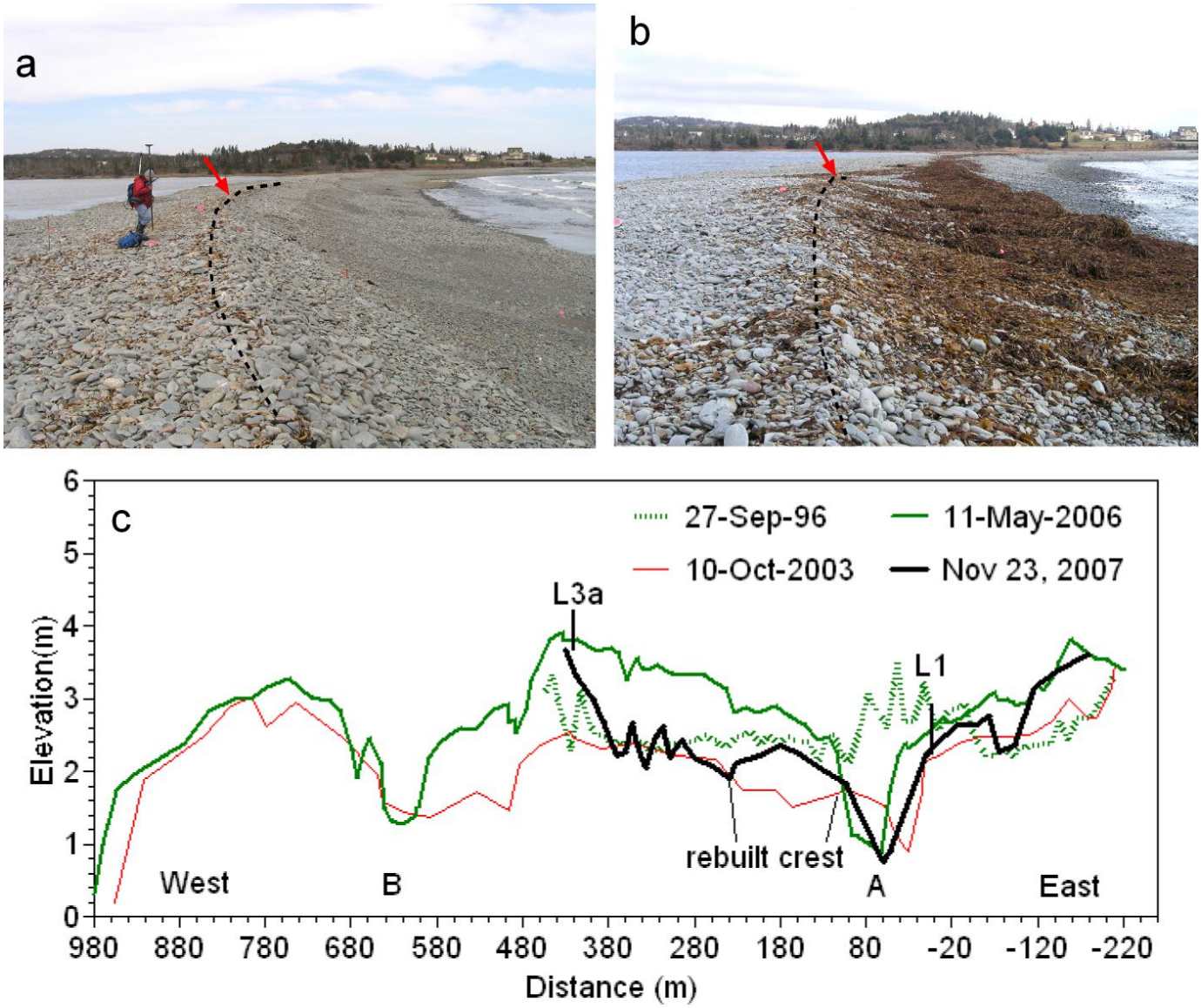


Figure 8a,b. Views looking east along Cow Bay Beach at survey line 1 in (a) June 2007 and (b) Nov. 23, 2007 after Noel showing the new lobe of sediment (arrow) deposited in the pond and the change in surface sediment texture. The same marker on line 1 is circled on both photos for visual reference. (photos P1010067, PB230837, R. Taylor).

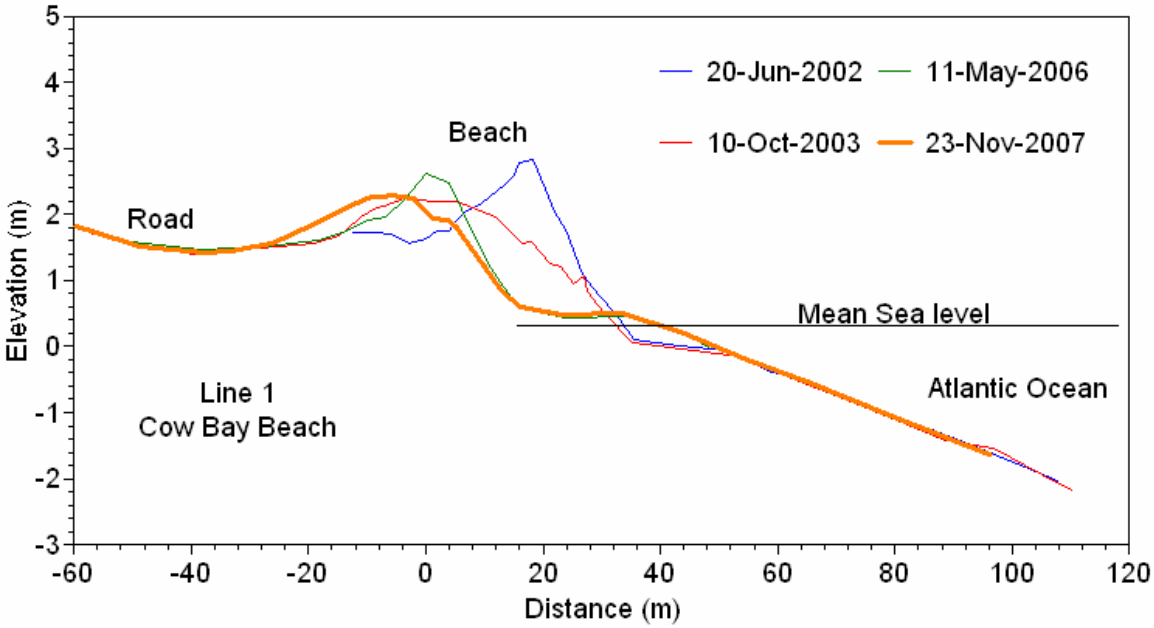


Figure 8c. Sequence of cross-shore beach changes at line 1 Cow Bay Beach resulting from Hurricane Juan in October 2003 and Post-tropical Storm Noel in November 2007. The beach crest is built up after each major storm but it moves farther landward.

SUMMARY- Cow Bay Beach -low gravel barrier

During Noel, waves flowed over all but a few small areas (>3.9m) of the beach and through two channels into Cow Bay Lake and continued the natural rapid breakdown and landward migration of this beach. The beach was flattened and lowered to an elevation observed after Hurricanes Hortense and Juan. After all events, the beach naturally recovered and was rebuilt, albeit farther inland. Beach migration has accelerated by nearly 3 times, from a mean of 1.8 m/a (1991-01) to 4.8 m/yr (2002-07) which causes a decrease in substrate compaction and stability. The beach can rebuild but there is increased potential for further rapid retreat and complete barrier collapse in future storms.

Conrads Beach, Halifax County

Conrads Beach is a mainly sand beach complex, that developed in the lee of a headland that extended offshore at Fox Island. Between 1962 and 1989 large quantities of sand and gravel were swept inland through a tidal channel that formed between lines 7 and 4 (Fig. 9). Since the natural sediment infill of the tidal inlet the beach has been building seaward at 3 to 6m/year.

Figure 9. Location map of cross-shore survey lines 1 to 7 established on Conrads Beach in the 1980s. Lines (L) 2 and 4 were resurveyed following Post-tropical Storm Noel on Nov 6, 2007. (Digital 2003 air photo 4460633 & 4465633, courtesy NS Department of Natural Resources).

Seawater flooded low parts of Conrad Road leading to Conrads Beach and water backed up around the bridge at the parking lot flooding parts of the marsh but the boardwalk from the parking lot to the beach was not damaged as it was in Juan. There was localized wave scouring around the boardwalk at the beach but much of it was protected from waves by a thick cover of sand dune. By Nov. 22, Nova Scotia highways had armoured and widened the seaward shoulder of Conrads Road. Along the beach, wave runup extended nearly to the crest of the primary dune at 3.6 m to 4.0 m elevation, similar to the level reached during Hurricane Juan.

Water flowed farther inland through low-lying parts of the dune, such as through the former excavation pit east of line 1 and across the low natural backshore west of line 4 where the inlet used to exist. Waves washed over the dune grass for tens of metres, gradually seeping into the ground, not forming washover channels. Large debris lying in the low backshore along the western beach was transported farther inland with cut grass

but causing little scour. The dense dune grass protected the backshore from wave scouring.

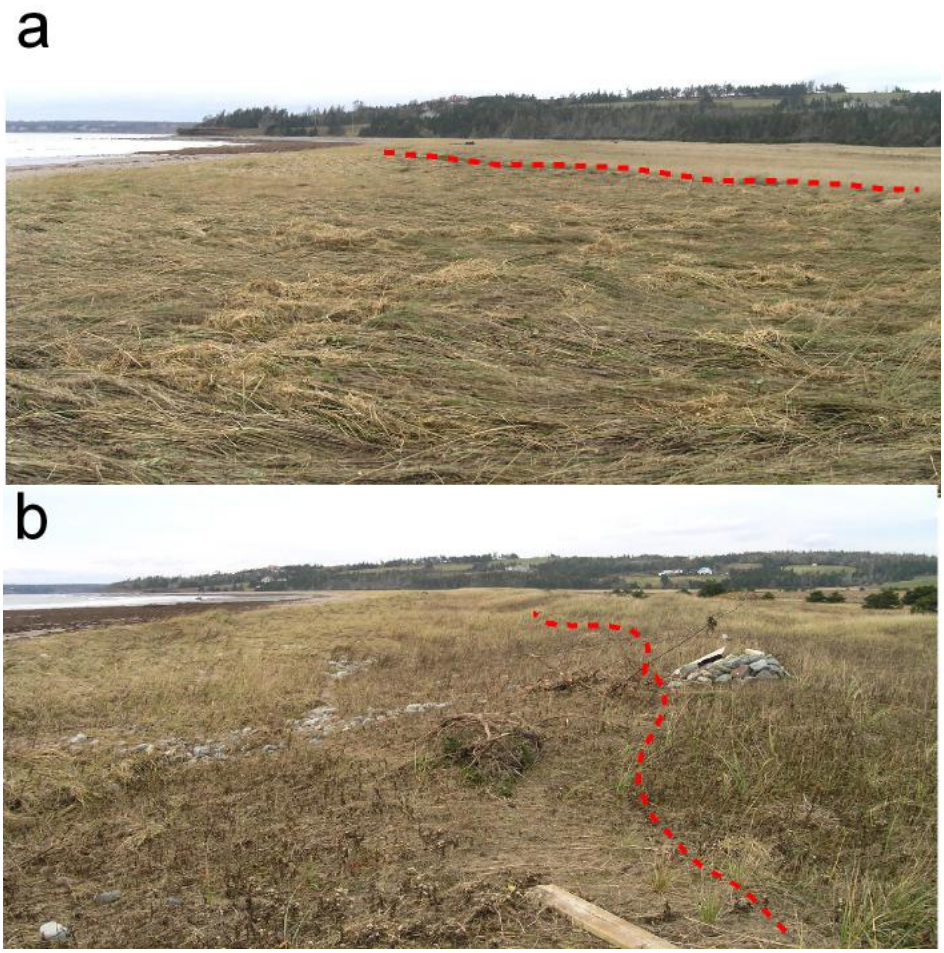


Figure10. Extent and impacts of wave overwash on the backshore dunes at Conrads Beach (a) across the low backshore west of Line 4 where dense marram grass was flattened as it dissipated the flood water and incurred little damage and (b) across the higher dunes between Lines 1 and 2 where flotsam and pebble- cobble were deposited to 3.6 m to 4.0 m elevation. (photos PB060467, PB060439, Nov.7, 2007, R. Taylor).

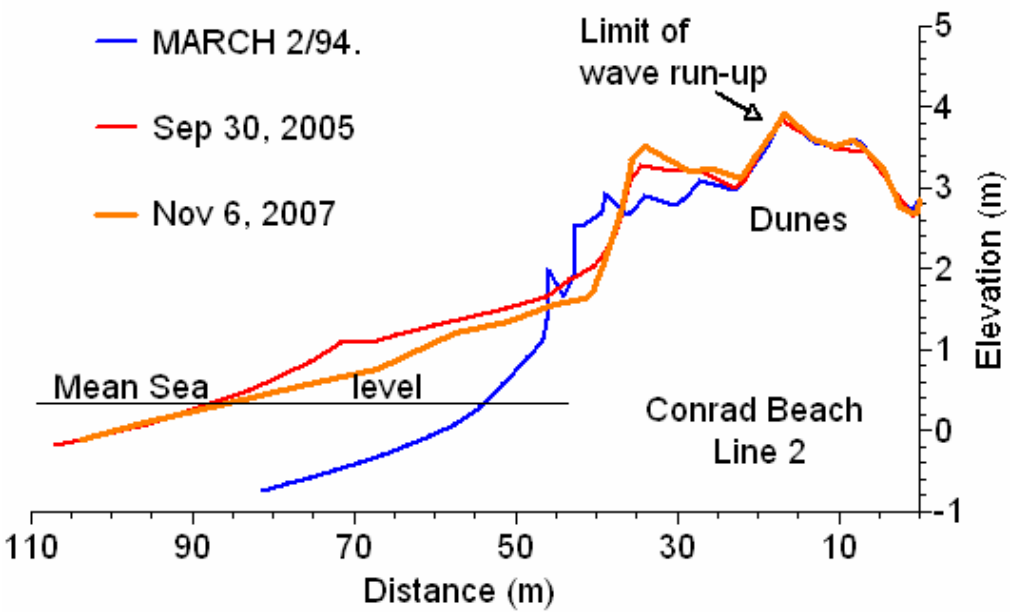
A pebble-cobble ridge along the base of the seaward dunes, which had been gradually buried by sand since Hurricane Juan, was re-exposed alongshore from Line 1 to nearly Line 3 where thicker dune was scarped back. Sand levels across the smoothed featureless beach remained high.

It is more difficult to differentiate the specific impacts of Noel at Conrads Beach because of the lack of recent cross-shore surveys. The most recent survey before Noel was in 2005. However, based on recent photos, beach morphology and debris indicators, it is concluded that the beach slope was combed down possibly by as much as 0.3 m and a pebble-cobble ridge at the base of the seaward dune was re-exposed as water flowed into

the dunes. Since 2005 the seaward dune crest was built up by 0.13 to 0.23 m. Water flowing over the dunes flattened the grass and may have slightly lowered the dune crest, however there was no net loss of dunes since 2005 at the two sites surveyed. No observations were made along the beach east of Fox Point.

Figure 11. Conrads Beach, line 2 on (a) Dec 25, 2006 when sand had accumulated across the upper beach and (b) Nov 6, 2007 after Post-tropical Storm Noel (blue pack for scale). Waves flowed over the dunes, scoured the sand cover exposing a pebble-cobble deposit which protected the dune from scouring. (photos PC250008, & PB060451, R. Taylor)

Figure 12. Selected cross-shore surveys from Line 2 Conrads Beach showing the accumulation of sediment across the beach and dune since 1994 and the minor net loss of sediment since 2005. Figure 11a indicates that more sand accumulated after 2005 so the total loss of sediment during Noel was greater than the surveys indicate.



The state of the backshore dunes and vegetation cover on Conrads Beach prior to Noel was sufficiently well established to have withstood the negative impacts of the storm and has been further built up in some low areas as sediment and debris were deposited by wave run-up. Since 2002 the foredune has increased by 1.6 m in width and become just shy of the elevation of the primary dune at line 2. Dunes most impacted by waves during Noel were those that had grown the most in the past few years, such as at line 3. They presented a steeper slope which waves cut back as a scarp.

SUMMARY- Conrads Beach -mixed sand and gravel barrier with dunes

Localized wave scouring occurred at the boardwalk, steep dunes and along the access road to the beach. Wave run-up across more gradual sloping dunes reached 4 m (CGVD28) similar to Hurricane Juan. Upper beach and foredune were lowered exposing a pebble cobble storm ridge built during the 1990s. Much of Conrads Beach is in a natural building phase which was only slightly interrupted by Noel.

Lawrencetown Beach, Halifax County

Lawrencetown Beach is a 1.8 km long mixed sand and gravel barrier which fronts Lawrencetown Lake. The beach is a provincial park east to Wyndenfog Lane where private residences exist. Backshore dunes vary in elevation from less than 4 m to just over 6m. Red and orange arrows mark approximate areas where water flowed through the dunes into the backshore during Noel. Surveys were completed at all seven cross-shore lines on Nov. 5-6, 2007 to assess the impacts of Noel (photo Oct/Nov. 2003).

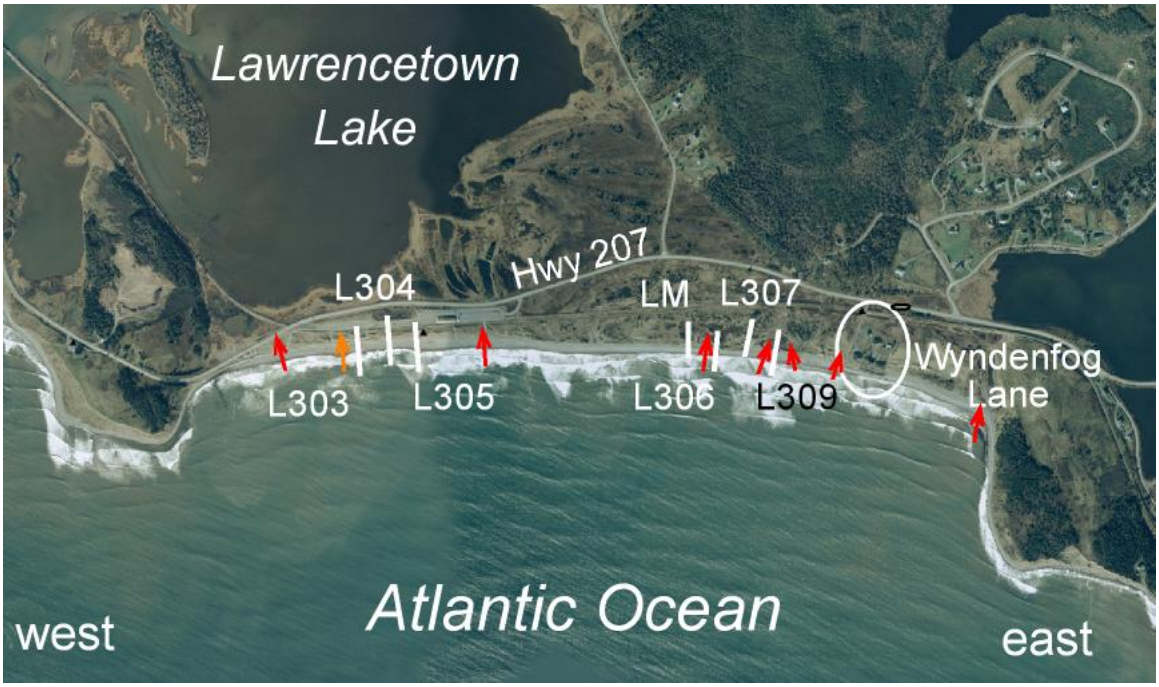


Figure13. Location map of cross-shore lines resurveyed on Lawrencetown Beach following Post -tropical Storm Noel. Red and orange (Fig 14a) arrows show approximate locations where water flowed over or through the dunes. (Digital 2003 air photo 4460633 & 4465633, courtesy NS Department of Natural Resources).

Boardwalks at the west end of the Lawrencetown , back of the armour rock and those crossing to the beach were damaged and scoured by waves. Rocks were tossed over and through the armour rock onto the highway and wave overwash in this area caused one driver to go off the road and abandon his vehicle as he was hit by water. Flooding at the east end of the beach at Wyndenfog Lane reached the garage doors and nearly the base of the front steps (1.94 m CGVD28) of # 1 Wyndenfog Lane by the morning of Nov. 4 at 08:30 AST (Fig. 4).

Primary weak points (Fig 13 red and orange arrows) along the beach where water and debris flowed farthest inland were observed at low dune areas at the west end of the beach, east and west of the parks canteen, and where dune craters exist along the

backshore such as west of Wyndenfog Lane. These are key vulnerable spots to monitor during future storms.

Figure 14. Views of wave overwash across dunes at the west end of Lawrencetown Beach (a) a low area where channelised flow carried pebble-cobble to the parking lot (Fig. 13 orange arrow) and b) sheet washover of gravel and partial burial of an abandoned vehicle (photos PB170727 R. Taylor and 154116, D.L. Forbes, 4 Nov. 2007).

Along western Lawrencetown Beach, between survey lines 303 and 305 where the backshore dunes are higher, the main wave run-up marked by drift lines with large pieces of wood reached elevations of 4.9 m to 5.8 m. Waves in places reached the dune crest at 6.0 m to 6.3 m elevation and flowed along the path where the boardwalk once existed and down the back slope of the dune. There was localized scouring at trails and boardwalks and debris and cobbles were carried through or over the lowest parts of the dune but little significant damage was observed from Noel. In general, dune retreat at the survey lines was much less than in Juan with a few exceptions. For example the metal boiler in the dune face was exposed more during Noel and dunes west of line 303 appeared more eroded. Dune retreat during Hurricane Juan was 5 m to 18 m whereas during Noel it was a maximum of 1.1 m on the survey lines.

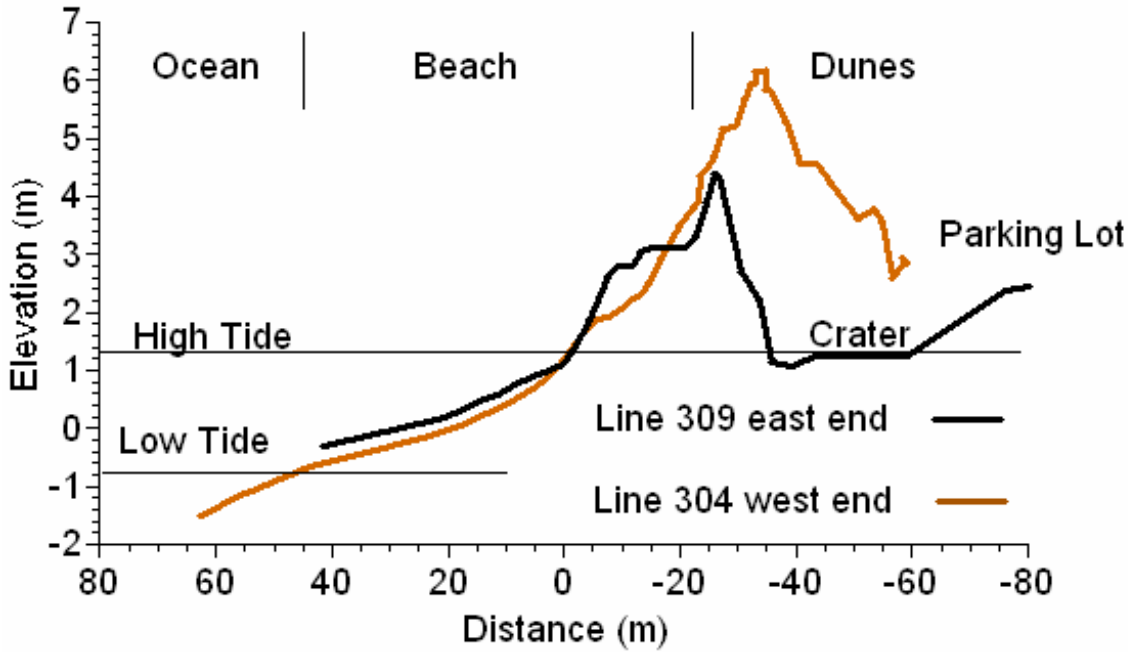


Figure 15. Comparison of the size of backshore dunes at the east and west end of Lawrencetown Beach. During Noel water flowed over the top of the dunes at Line 309 and reached 6 to 6.3 m elevation along the dune crest at Line 304. The greatest changes were observed across the upper beach at 2 to 4 m elevation. In the east the pebble-cobble storm ridge was pushed landward into the low backshore whereas along the west beach pebble-cobble was mostly combed downslope and only transported landward where the dune was low or non-existant. Between survey lines 303 and 305 a rhythmic pattern of beach cusps was observed with a wavelength of approx. 80-100m.

Figure 16. View of boardwalk just west of Line 303 where waves scoured a significant portion of beach and dune as indicated by the former ground surface marked by a stain line (arrows) on the support posts (photo PB050359, R. Taylor).

Along the eastern portion of Lawrencetown Beach, between survey lines M and 309, water freely flowed into the backshore where the beach /dune crest was less than 4.5 m. Where the dune was extremely narrow waves rolled back the grass edge and flowed over the dune to an elevation of 4.9 m. Flooding of the backshore craters reached 2.5 to 3.0 m elevation and grass and smaller wood debris were carried as much as 84 m landward of high tide level into low backshore areas (elevation of 2.6 m). Water also flowed inland past the old railway embankment through a gully adjacent to the Moonlight Bed and Breakfast at Wyndenfog Lane (Fig. 4c, 13) and into the backshore through the east end of the beach as mentioned above.

The most significant impact on dunes on the eastern part of Lawrencetown Beach was a 2 m deep cut through the narrow dune adjacent to line 306. Since Juan the dune crest had retreated by 1.9 m and been narrowed by wave scouring on its back side. In April 2007 there was only a thin cover of pebble over relic sand dune which may have offered a weakened site for waves to scour the channel that formed during Noel.

A breach 7.0 to 8.4 m wide was cut through the dunes at 4.2 m elevation. The base of the breach was 2.1 m CGVD28. The floor of the backshore crater lay at 1.73 m and estimated higher high tide level is 1.3 m, which means that following the storm, water only flows through the breach near high tide or when larger waves occur. The new channel was similar to the cut made during Hurricane Juan through the dunes at L307. Since 2003 the cut at L307 was widened and a pebble cobble ridge developed along the top of the beach. During Noel the pebble-cobble ridge was scoured down to 2.6 m elevation which enabled water to infill the adjacent crater back of L309.

Changes across the beach differed between the eastern and western parts of Lawrencetown Beach mainly because of the difference in the backshore character. Along the western portion of the beach where a higher dune exists, waves may reflect off the dune creating a more rhythmic pattern of longshore change. For example, a pebble-cobble storm ridge built at the base of the dunes between 2003 and 2007 was combed downslope at line 304 during the April 2007 storm and built higher at line 303. During Noel the upper beach between line 303 and 304 (~ 80-90 m wide) was scoured down removing the pebble -cobble ridge from line 303 and less sediment from line 304. The cobble ridge only survived west of line 303 and at line 305. At both lines 303 and 304 the beach was scoured down to the same level they were during Hurricane Juan.

Along the eastern part of the beach, waves smoothed the upper beach slope and pushed the pebble-cobble crest landward covering and infilling the backshore dunes. Net landward beach crest retreat was least at line M and most at line 307 where it was pushed 3.6 m landward (Fig.19). Along all but the highest dune areas, pebble -cobble gravel and other debris covered the backshore dune and craters. Where craters existed back of the primary dune (e.g. at line 306), overwash scoured the landward side of the dune, decreasing the dune width. The scouring has left the dune very vulnerable to break-through during future storms, as we observed during Noel at line 306.

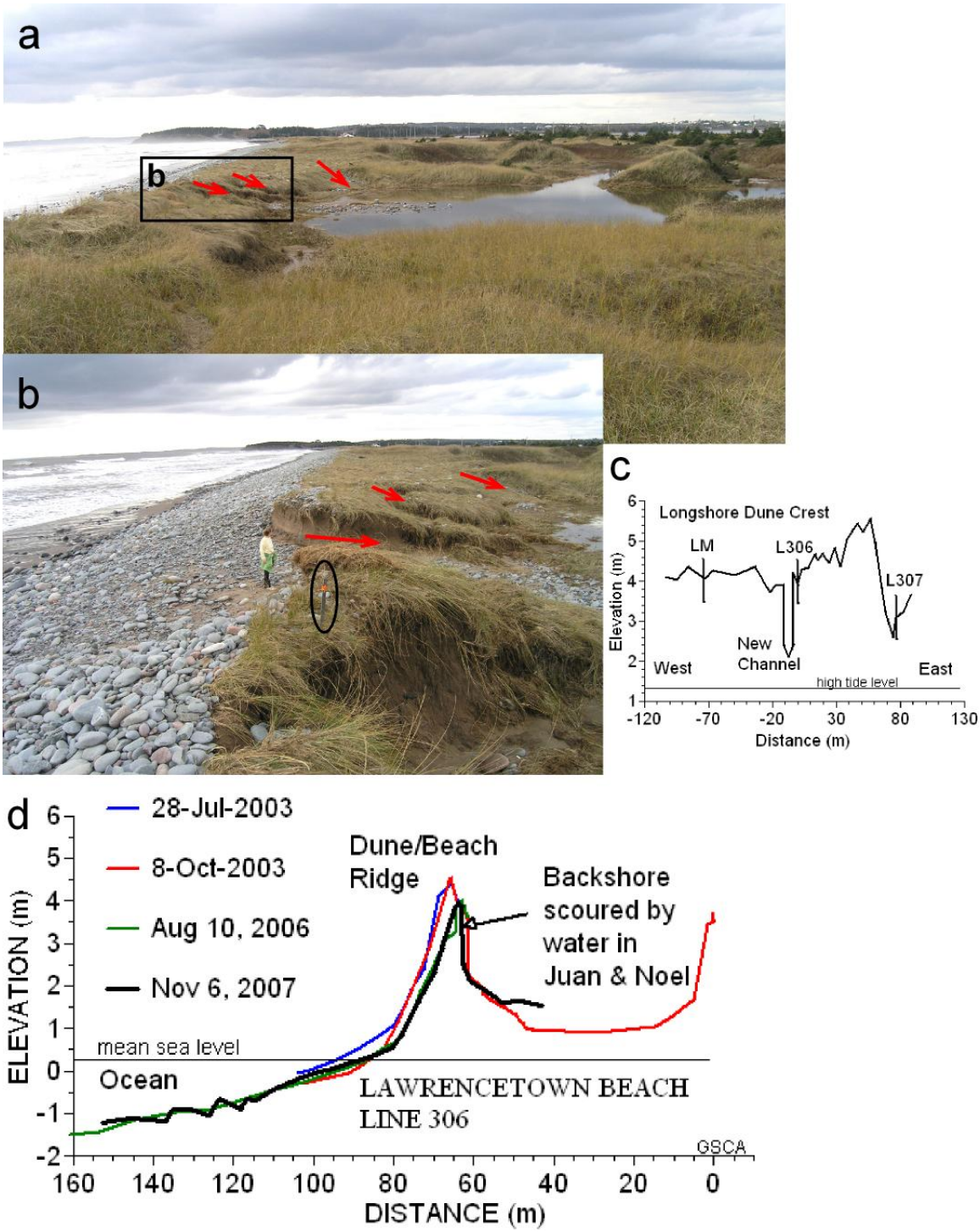


Figure 17. (a) View of dunes and large craters at east end of Lawrencetown Beach where waves overwashed the narrow dune, scouring its backslope (arrows), and (b) close-up of channel cut through the dunes just west of survey line 306 (T-bar circled). (c) longshore crest profile from line M to line 307 showing the spacing of dune cuts which is approx 80 m. (d) Repetitive surveys at line 306 illustrate the decreasing size of the dune since 2003 making it vulnerable to scouring and destruction during Noel (photos PB050388, PB050396, R. Taylor, Nov. 5).

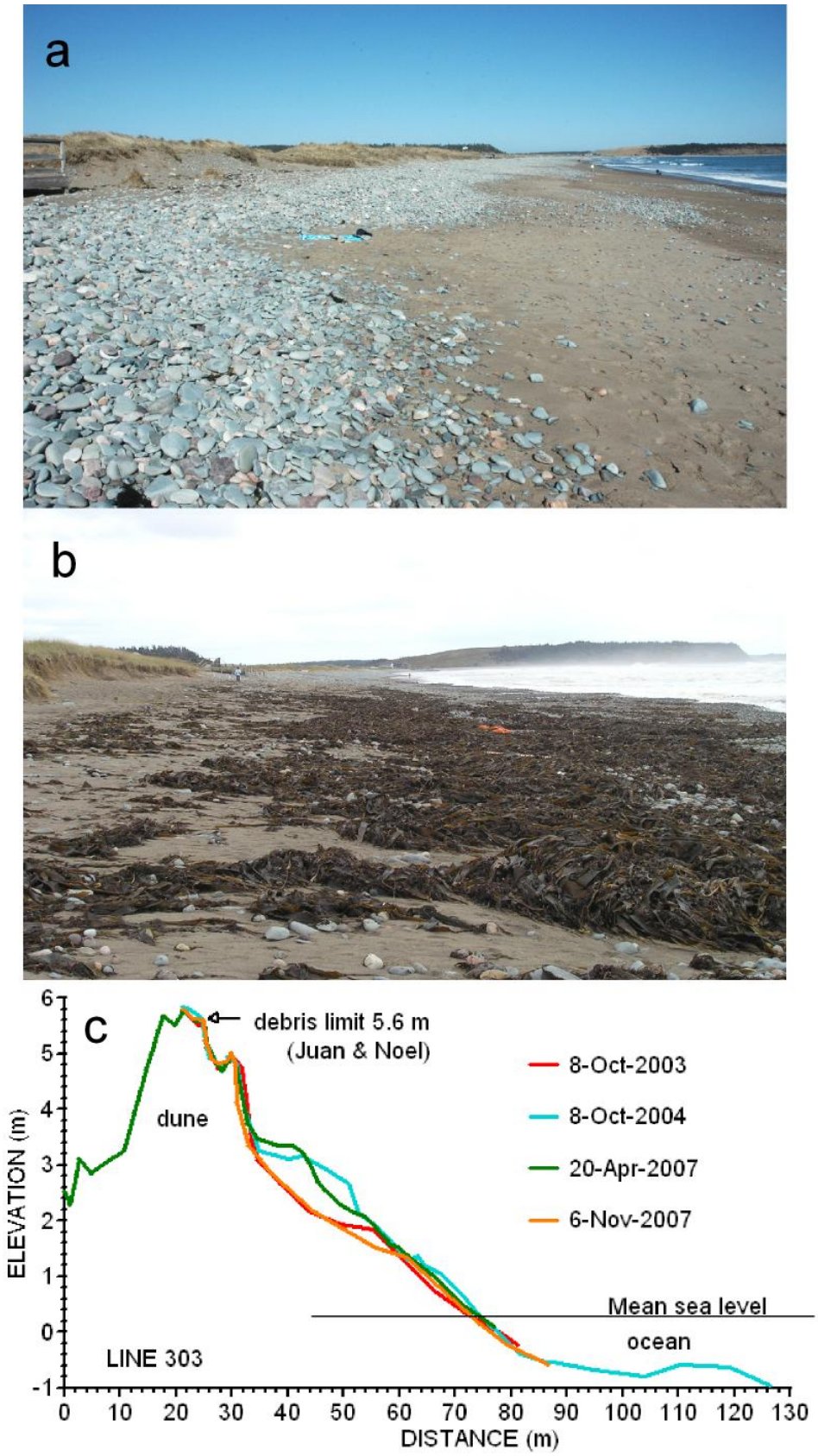
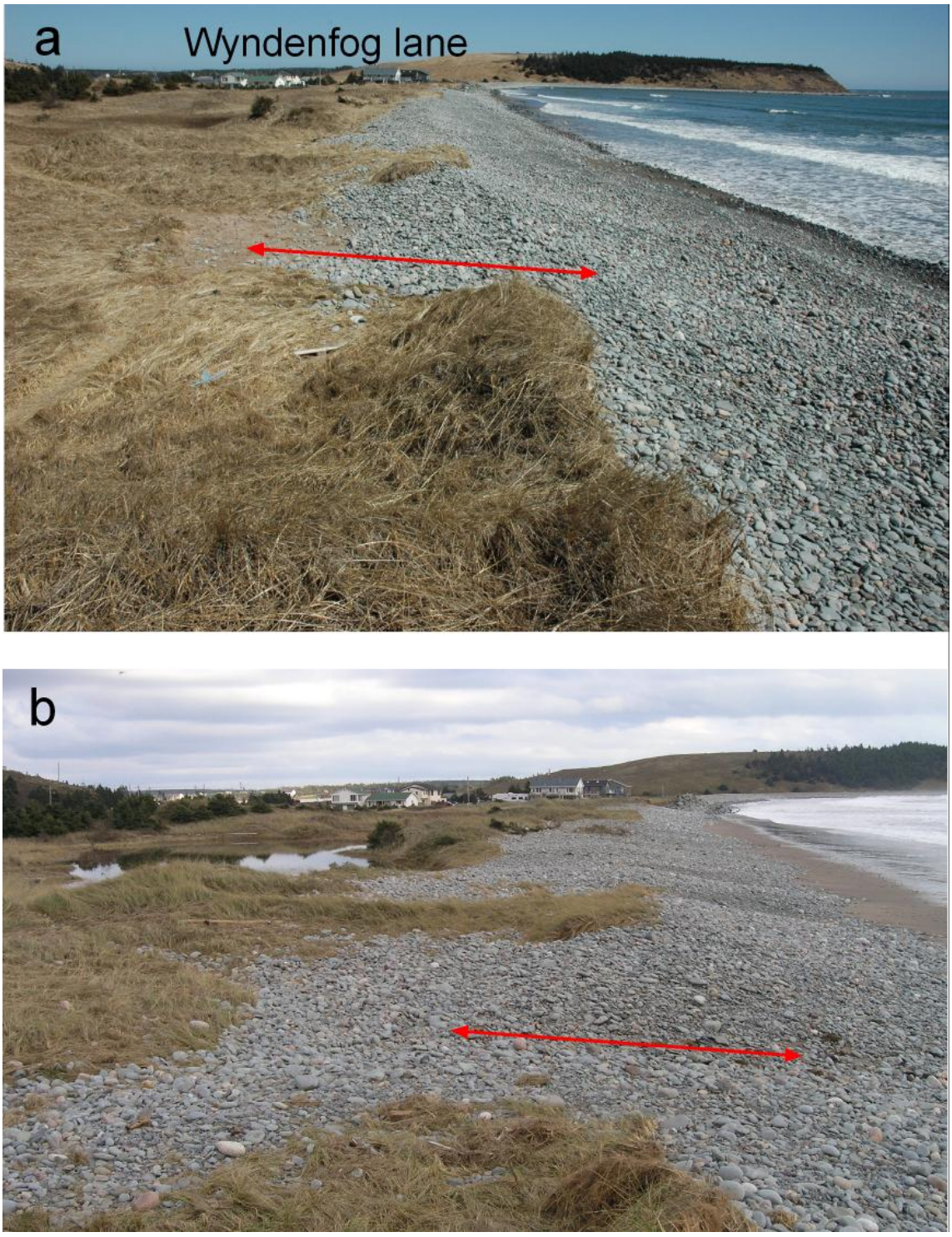
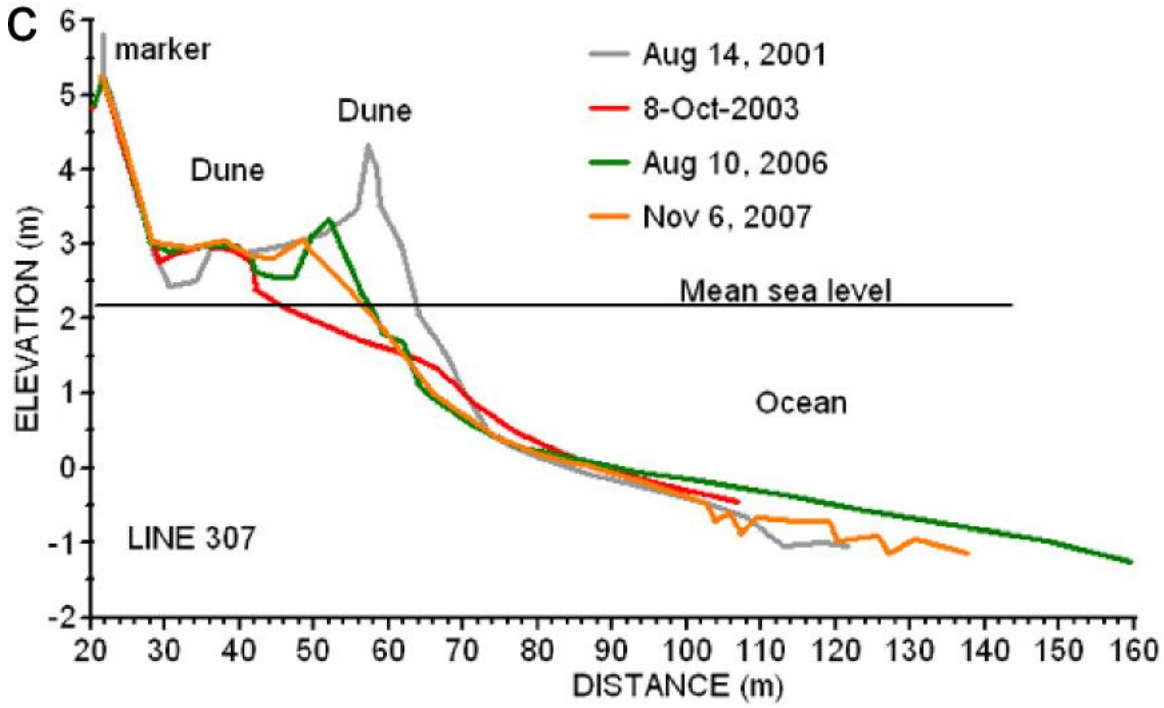


Figure 18. Views of Lawrencetown Beach at line 303 where a large pebble -cobble storm ridge built against the dune after 2003, as shown in (a) Oct. 2004. It was modified in April 2007 and erased (b) during Noel in Nov. 2007; (c) Repetitive cross-shore surveys at line 303 illustrate the similarity in upper beach scouring during Noel and Hurricane Juan (photos 35-8-2004 and PB050348, R. Taylor).

Figure 19. View of east end of Lawrencetown Beach at line 307 (arrow), (a) in April 2007, before Noel, and (b) Nov. 5, after Noel, where cobble is accumulating overtop of low dunes and (c) cross-shore surveys showing the major loss of dune during Hurricane Juan in 2003 and the subsequent landward beach migration. (photos 174416, D.L. Forbes Apr. 20 & PB050385, R. Taylor, Nov.5, 2007).





SUMMARY- Lawrencetown Beach -mixed sand and gravel barrier with dunes

Water flowed through and over low (< 4.5 m elevation) dunes at several locations as much as 84 m inland from high tide limit. A channel was cut through a narrow dune linking the ocean to low backshore area. Wave run-up extended to 6.3 m elevation across higher dunes. Backshore flood level was 1.94 m (CGVD28). Localized beach and dune scouring occurred at boardwalks and trails. In the west, the upper beach was scoured to similar levels as after Hurricane Juan, and in the east, beach pebble cobble was pushed landward 3 to 4 m over low dunes as part of the natural landward shoreline migration. Little significant damage to overall beach system but weak areas developing, warning of potential larger changes in future storms of similar magnitude.

Miseners - Long Beach, Halifax County

Miseners-Long beach is a 1.7 km long, 40-60m wide, high gravel barrier fronting Meisners Lake. On November 7, 2007 cross-shore lines L0, L2 and L4 and the beach crest from the west end of the beach to just east of line 4 were resurveyed to assess the impacts of Noel (Fig. 20, 21b). The largest physical changes were observed between line 2 and line 3. Previous surveys across the beach were in July 2007 and along the beach were in May 2007.

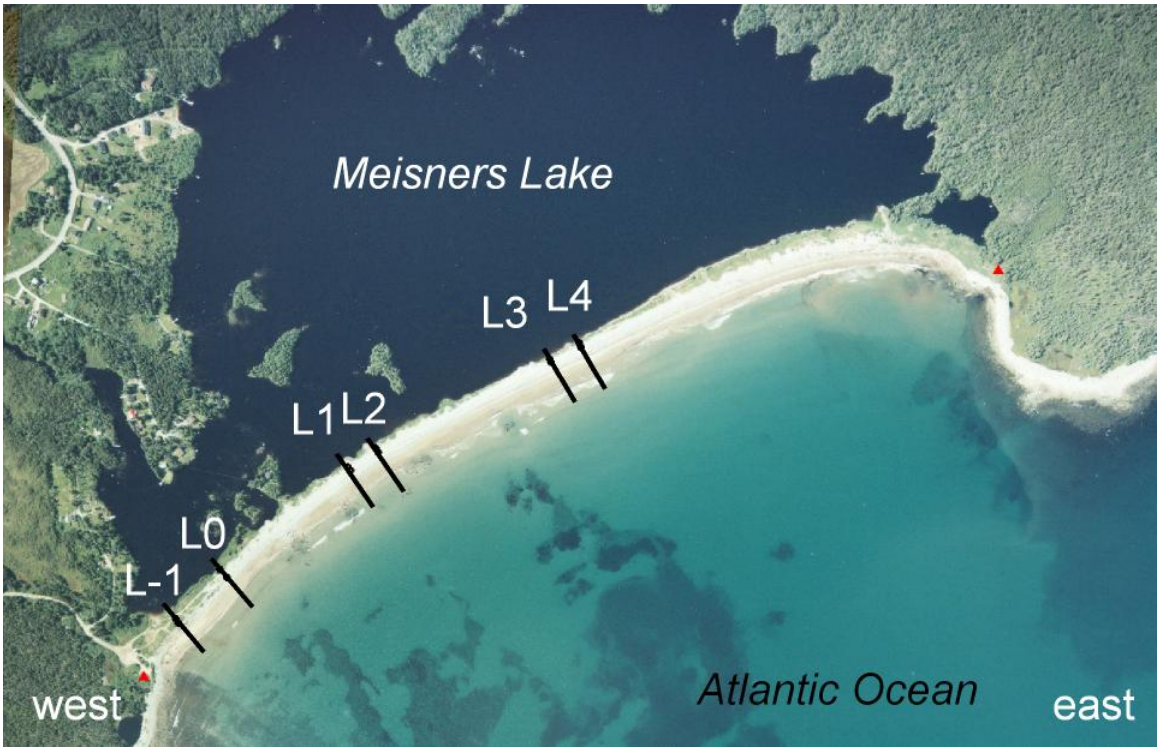


Figure 20. Location of cross-shore lines (L-1 to L4) which were resurveyed to document the impacts of Noel on Miseners-Long Beach. Red triangles mark horizontal survey control points. (airphoto 03306-7, 2003; NS Housing and Municipal Affairs).

Extensive deposits of cobble across the backshore, particularly at the west end of the beach suggested most of it had been overwashed by waves. In May 2007 before Noel struck the highest beach crest was in the vicinity of Lines 3 and 4 where it extended to 4.4 m. After Noel there was only a short segment of crest remaining above 4.4m. Changes along the crest and sediment deposition across the backshore indicate that waves easily overwashed the beach where the crest was less than 4 m but they also toppled a section of beach that was 4.4 m elevation. The beach crest was most impacted between lines 2 and 3 where it was lowered in elevation by an average of 0.46 m and a maximum of 0.64 m (Fig. 20). Elsewhere along the western beach, the crest was only lowered an average of 0.2m. In general beach crest lowering was not as extreme as during Hurricane Juan but the pattern of where it occurred was similar (Fig. 21).

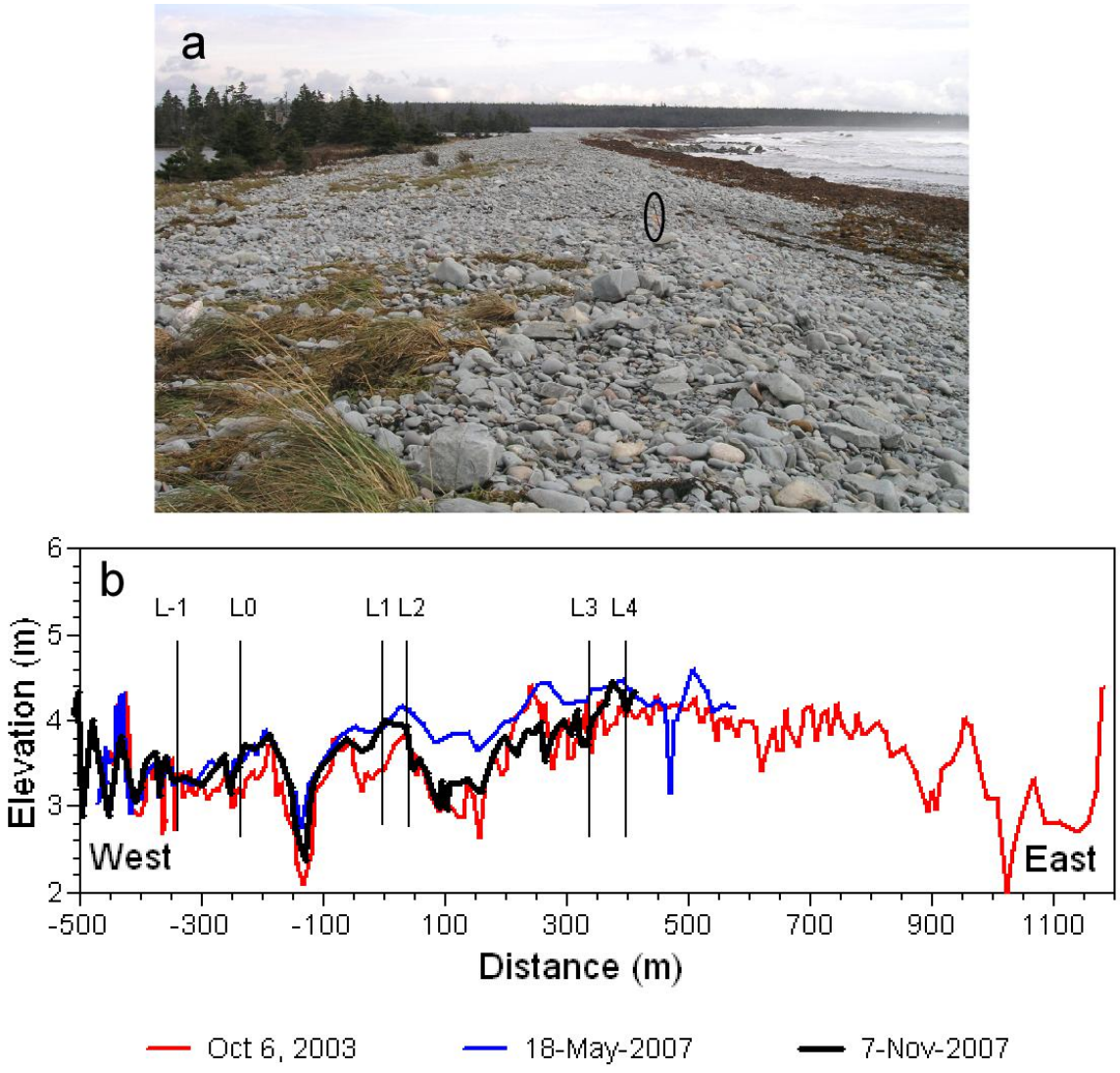


Figure 21. (a) View looking east along Miseners -Long beach on Nov. 7 at line -1 (marker circled) where the crest was lowered by 0.4 m and more of backshore grass was covered by cobble and (b) longshore crest profile with position of cross-shore survey lines illustrating the largest crest reduction was between lines 2 and 3. In general the crest was not lowered as much as following Hurricane Juan (photo PB070473, R. Taylor).

At Line 4 the crest had built seaward by nearly 0.7 m but was 0.1 m lower than in May 2007. The landward side of the crest was eroded suggesting either water flowed over the crest or the crest was rebuilt as the storm waned.

Across the barrier beach erosion of the upper beach slope and scouring at the base of the slope were common at all three survey locations. The largest change was at line 2 where the upper beach was eroded 2 m landward and a 1.1 m thick apron of sand was removed from the base of the beach.

Deposition of cobble across the backshore was greatest at the far western end of the beach and at Line 2 where nearly 0.4 m of cobble built up the backshore and extended into the pond (Fig. 22). At line 0 build-up across the backshore, was only sufficient to bury the old vehicle tracks (0.1 to 0.2 m). At line 4 the backshore showed little change on repetitive surveys however photos showed the backshore vegetation was nearly completely buried by cobble. (Fig. 23)

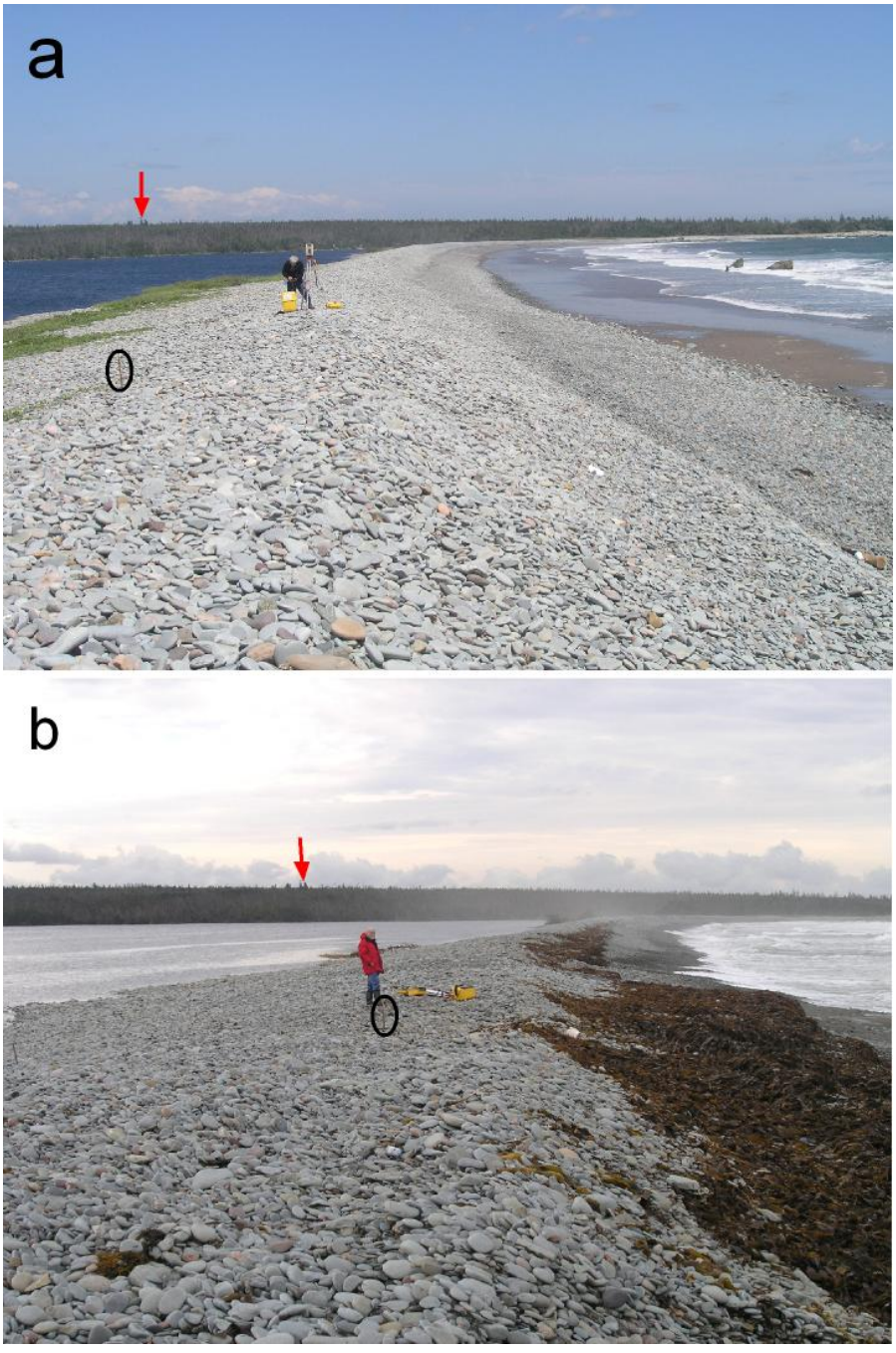
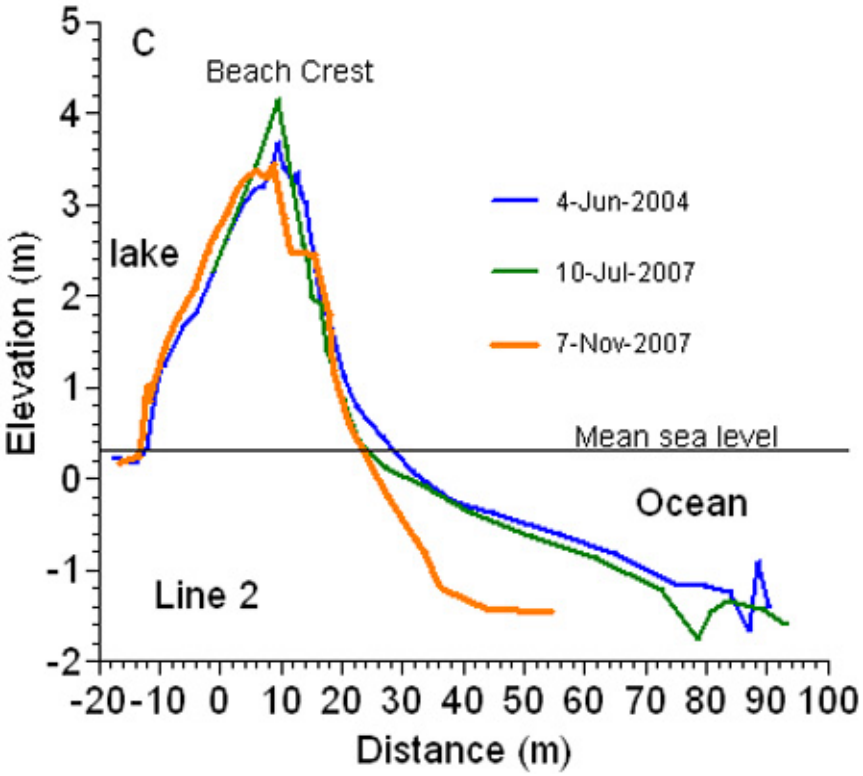


Figure 22. Views of changes caused by Noel at Line 2 Miseners -Long Beach (a) 13 July 2007; (b) Nov. 7, 2007.
By Nov. 7 a large quantity of seaweed was accumulating and protected the shoreline from further scouring.

Same line marker is circled in both photos and same trees are marked with an arrow for visual reference. (Photos P1010037, PB070490, R. Taylor)

Fig. 22 con't. (c) cross-shore profile showing sediment deposition across the backshore into the lake, barrier beach crest reduction and loss of sand at the lower beach slope.



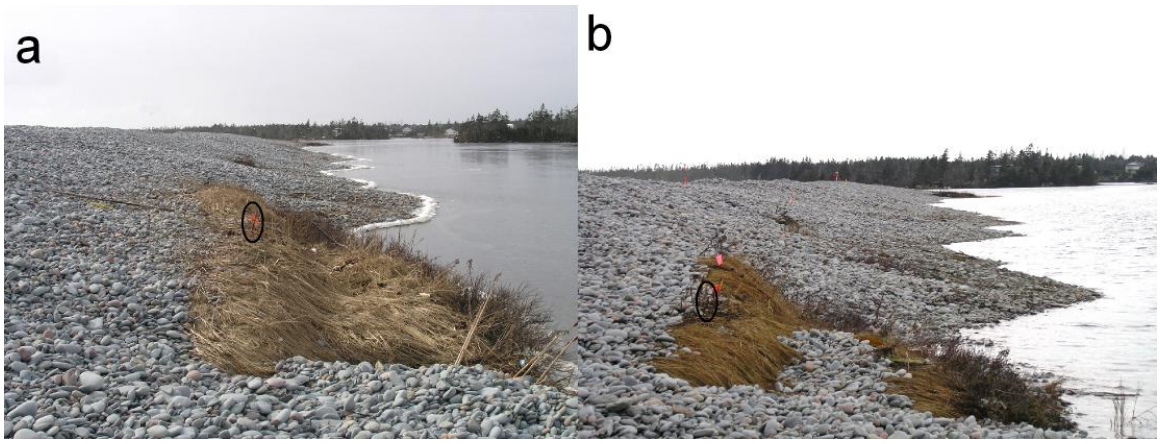
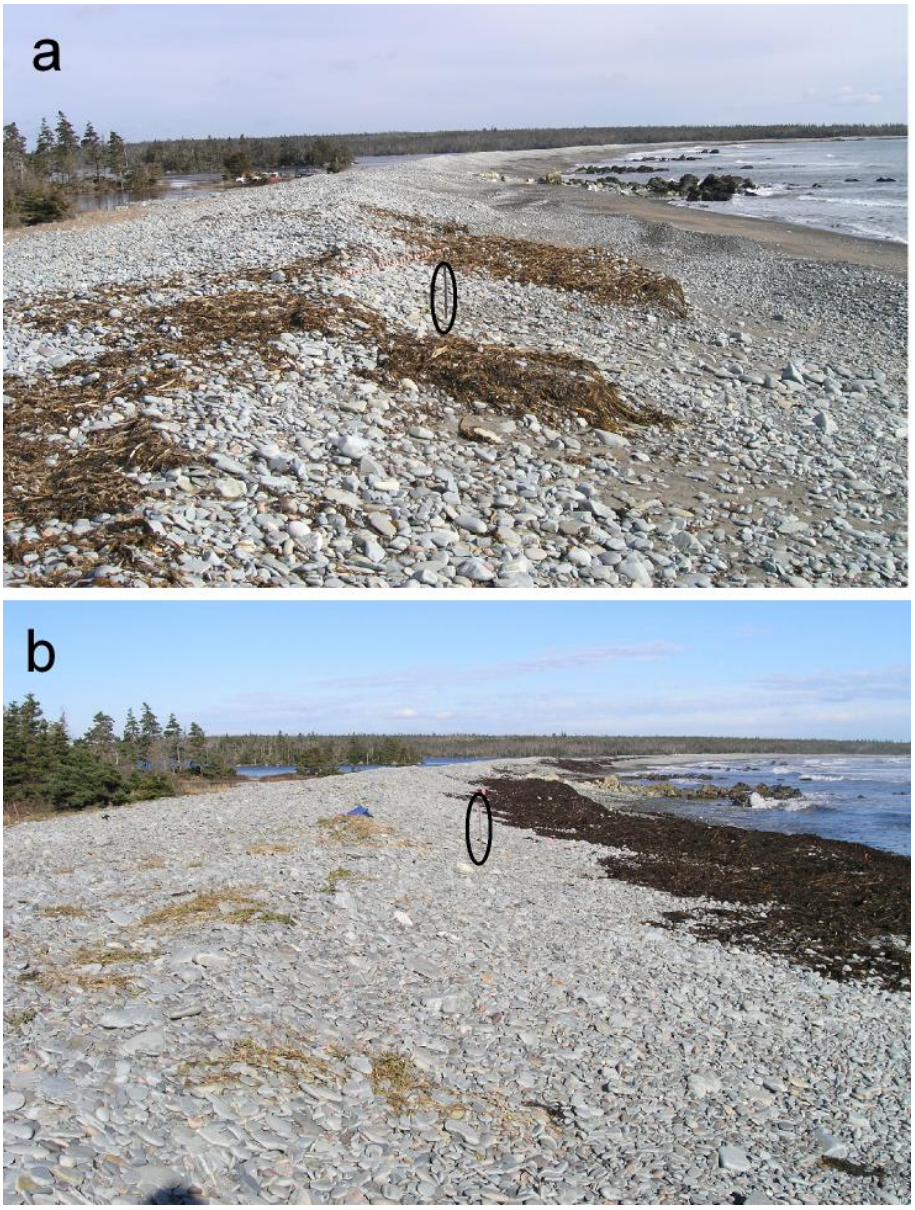


Figure 23. Views of the backshore at Line 4 before (a) winter 2006 and (b) after Noel showing the deposition of cobble and burial of the remaining backshore dune deposits. (Photos P2090038 and PB070510, R.Taylor).

Figure 24. Views of beach at Line 0 (line marker circled) (a) in September 2006 and (b) 7 Nov. 2007 showing conditions before and after Noel and (c) repetitive surveys across the beach showing gradual lowering of the beach crest, the volume of backshore sediment deposition from Noel compared with changes between 2001 to 2004 which included changes caused by Hurricane Juan (photos P2090012 and PB070524, R. Taylor).



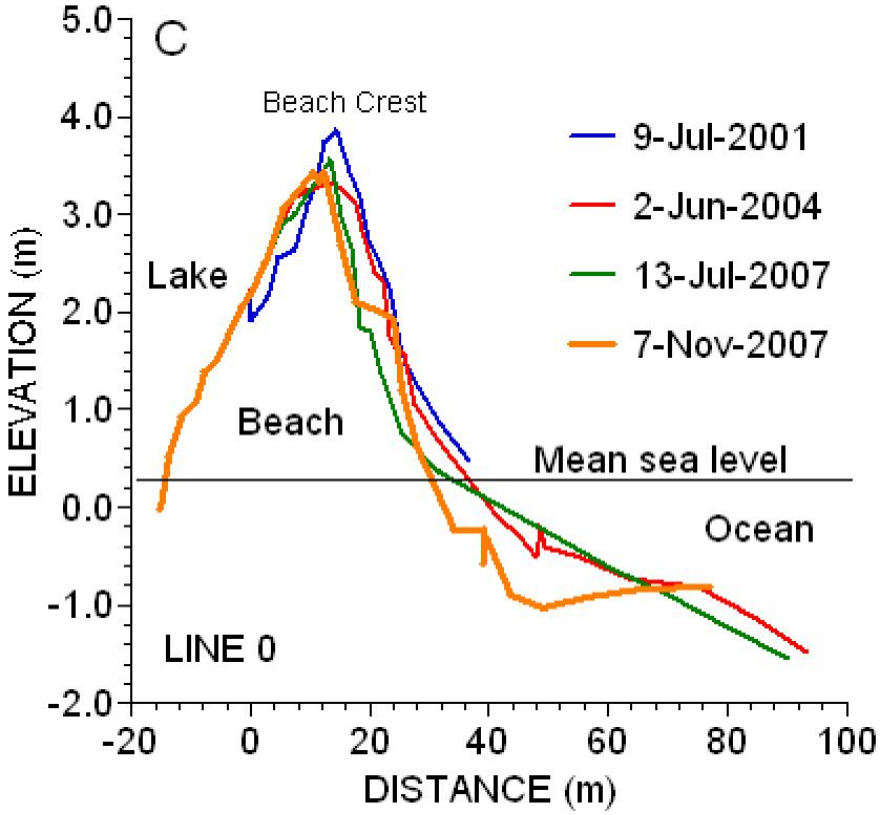


Figure 24 con't.

SUMMARY- Miseners -Long Beach -high gravel barrier

Waves overwashed most of the beach (≤ 4.4m, CGVD28) lowered the crest by 0.2 to 0.6 m, and cut it back by a maximum of 2 m, along its central section. The locations of beach crest lowering were much the same as during Hurricane Juan but the magnitude was less in Noel. Sediment, up to 0.4 m in thickness was deposited across the backshore to the pond. A thick (1.1m) accumulation of sand along the seaward base of the barrier was removed and carried offshore. Some large washover channels have become more persistent since Hurricane Juan and mark sites of future barrier weakness. Noel provided another small step in the natural lowering and landward migration of this high gravel barrier beach.

Martinique Beach, Halifax County

Martinique Beach is a 3.5km long sand barrier beach anchored by a series of rock outcrops such as at Whale Point (Fig. 25). The beach is backed by a single, primary dune that increases in elevation from 3 m at the east and west ends of the beach to 5 m along the central part (line 4 to east of line 5, Fig. 25).

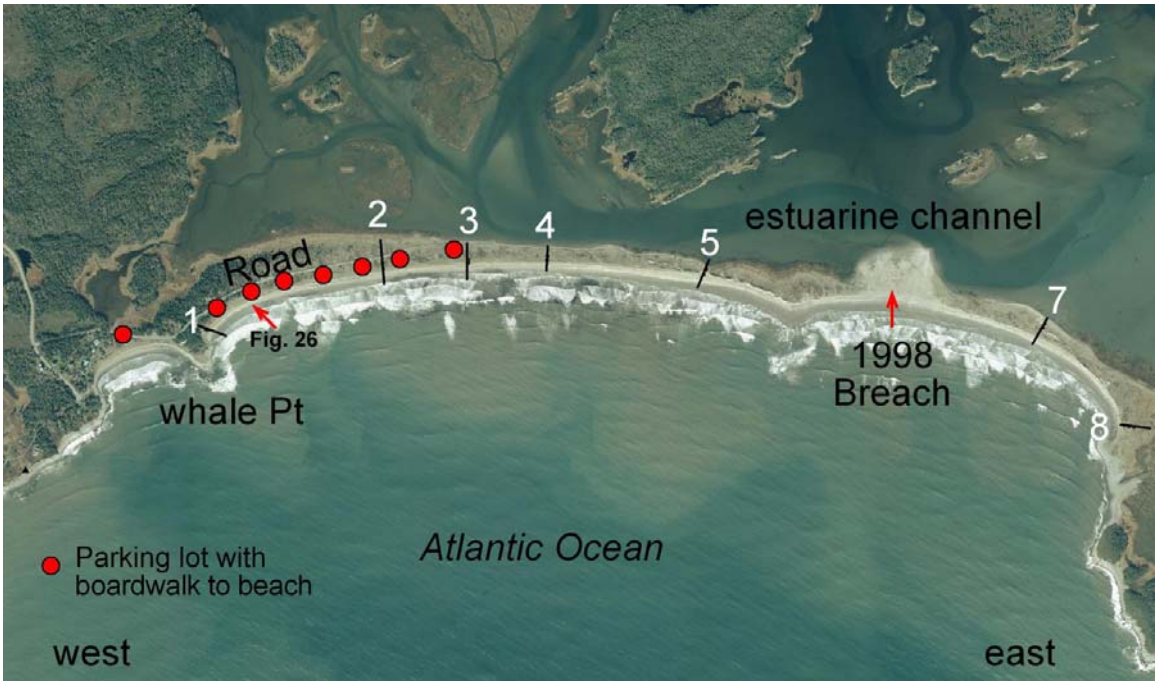


Fig. 25. Aerial view of Martinique Beach taken in 2003 showing the location of beach survey lines (1 to 8). The beach is more stable west of line 5 than farther east where channels have been cut through to the Musquodoboit River estuary in 1977 at line 7, in 1998 at line 6 (site of 1998 breach,), (Taylor and Frobel, 2005) and in Nov. 2007 at line 5 (Digital 2003 air photo 4465631, courtesy NS Department of Natural Resources).

The impacts from Noel were observed first on the afternoon of November 4 however detailed shore surveys of 4 cross-shore lines were not competed until November 21. The previous beach survey before Noel was completed in May 2007 at Lines 3 and 7 and in September 2005 at Lines 4 and 5. Photographs of select areas were available from September 2007.

The most dramatic impacts included damage to the beach access boardwalks and associated scouring of the adjacent dune (Fig. 26) deposition of wave overwash debris e.g. cobble, driftwood and grass across the backshore road and parking areas, the trimming and flattening of dune grass by waves (Fig. 27), and the cutting of a narrow breach through the dunes to the backshore estuary at cross-shore line 5 (Fig. 28).

The dune crest was overwashed by waves where it was 5 m or less in elevation. At the west end of the beach between the DNR park office and Line 1 where backshore elevations are less than 3.5 m debris was carried across the backshore to the road and was only hindered where bushes and trees existed. At lines 3 and 4 where crest elevations reach nearly 5 m debris lines only extended a few metres inland from the dune crest but where the crest was slightly lower, water flowed over the dune crest as much as 20 m downslope through dense marram grass before seeping into the dunes (Fig. 27b). Seawater flow was concentrated in the dune cuts adjacent beach access steps and in the 5-10 m wide overwash channel/ breach cut through the dunes at Line 5 (Fig. 28). The base of this channel was 1.6 m which is above high tide level whereas the base of the channel cut farther east in the winter of 1998 was much deeper at 0.1m elevation (Taylor and Frobel, 2005). It took 1 to 5 years before sufficient sediment built up the 1998 breach to reach an elevation of 1.6 m. There remains a chance for natural rebuilding or infilling of the washover channel at Line 5 as long as it is not widened or scoured down further during a storm this coming winter. Nevertheless the backshore dunes at this location are very narrow and vulnerable to breaching in future storms.

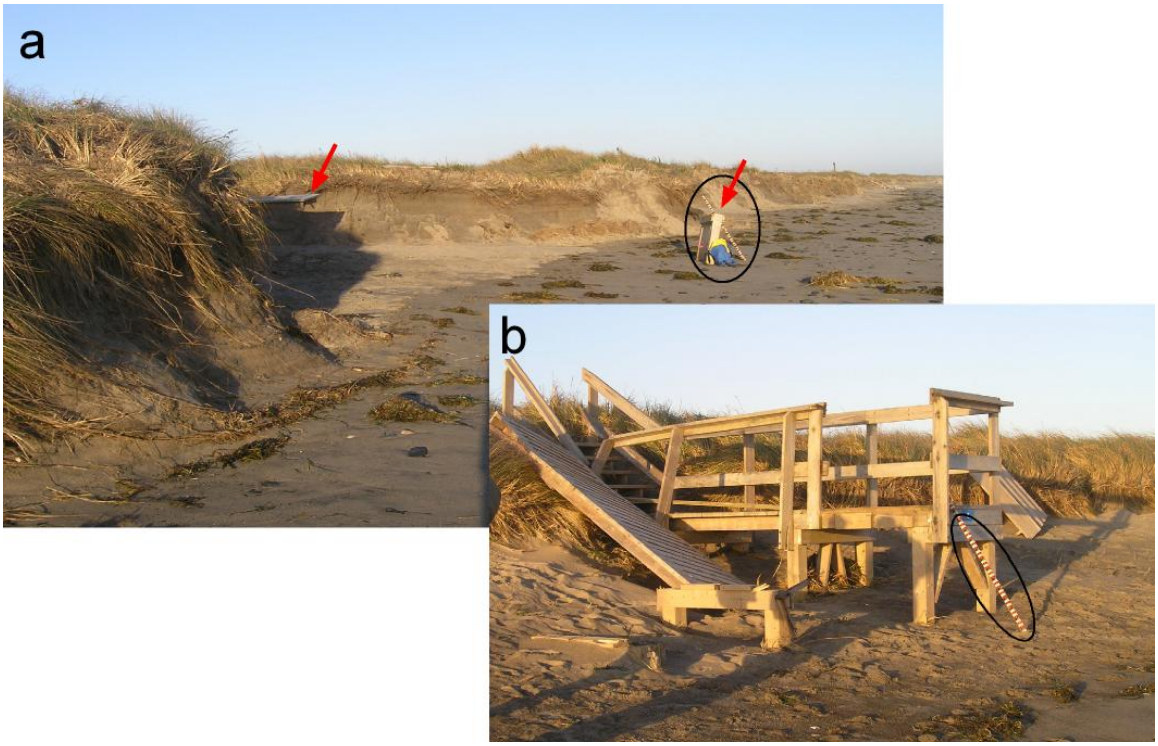


Figure 26. Damage to boardwalks on Martinique Beach varied depending upon their location and condition of beach prior to the storm (a) complete loss of platform (between arrows) between supports and severe scouring of adjacent dunes and b) tossing of access ramp against main boardwalk and steps into the dunes at parking area 8. Most large pieces of boardwalk broken away were carried toward the east end of the beach. A 1.5m long survey pole (circled) is provided for scale in each photo (photos PB040292 and PB040310, Nov. 4, 2007, R.Taylor).

Between May and November 2007 vegetated crest of the dune had actually extended as much as 4 m seaward and sediment had accumulated at the base of the dune scarp. Beach surveys in May 2007 reflected cuts in the beach and dune by winter storms, particularly a storm in mid -April. By September 2007 sand had infilled the upper beach and base of the dunes. At Line 5 sand had accumulated along sand fences and a healthy looking foredune was present (Fig. 28a). Therefore wave scouring during Noel was greater than the net changes revealed by our repetitive surveys. The largest beach changes were recorded at lines 5 and 7, toward the east end of Martinique Beach, where the upper beach ramp was scoured vertically downward by 1.2 m and at Line 5 the dune crest was lowered by as much as 2.9 m despite significant growth in the summer of 2007. The beach foreshore slope was cut back by a maximum of 8 m. In contrast where low dunes had built across the 1998 breach, water flowed through to the estuary shore in a couple of locations but the flow was reduced by dense marram grass. No surveys were available across the 1998 breach following Noel but photographs before and after the event suggest little change or possibly a buildup of sand and increased vegetation growth during 2007.

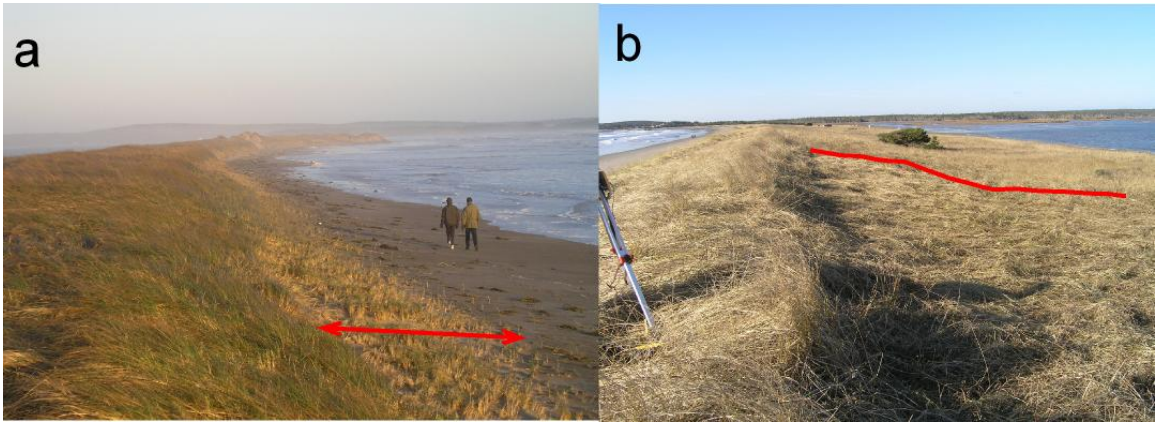


Figure 27. Views of Martinique Beach near line 4 where waves trimmed off the dune grass (a) (marked by arrows) and overwashed the dune crest at 5.1 m elevation. Seawater flattened the backshore grass (b) (edge of overwash outlined by line) with minor consequences (photos PB040330 Nov. 4, 2007 and PB210750 Nov. 21 2007, R. Taylor).

By late November 4th many pieces of boardwalk and steps had been transported long distances eastward (downdrift) along the beach and some large pieces were floated up into the dune cuts. By the time of our survey on November 21 sand was blowing back into the dune cuts, and the upper beach had been partially rebuilt by waves.

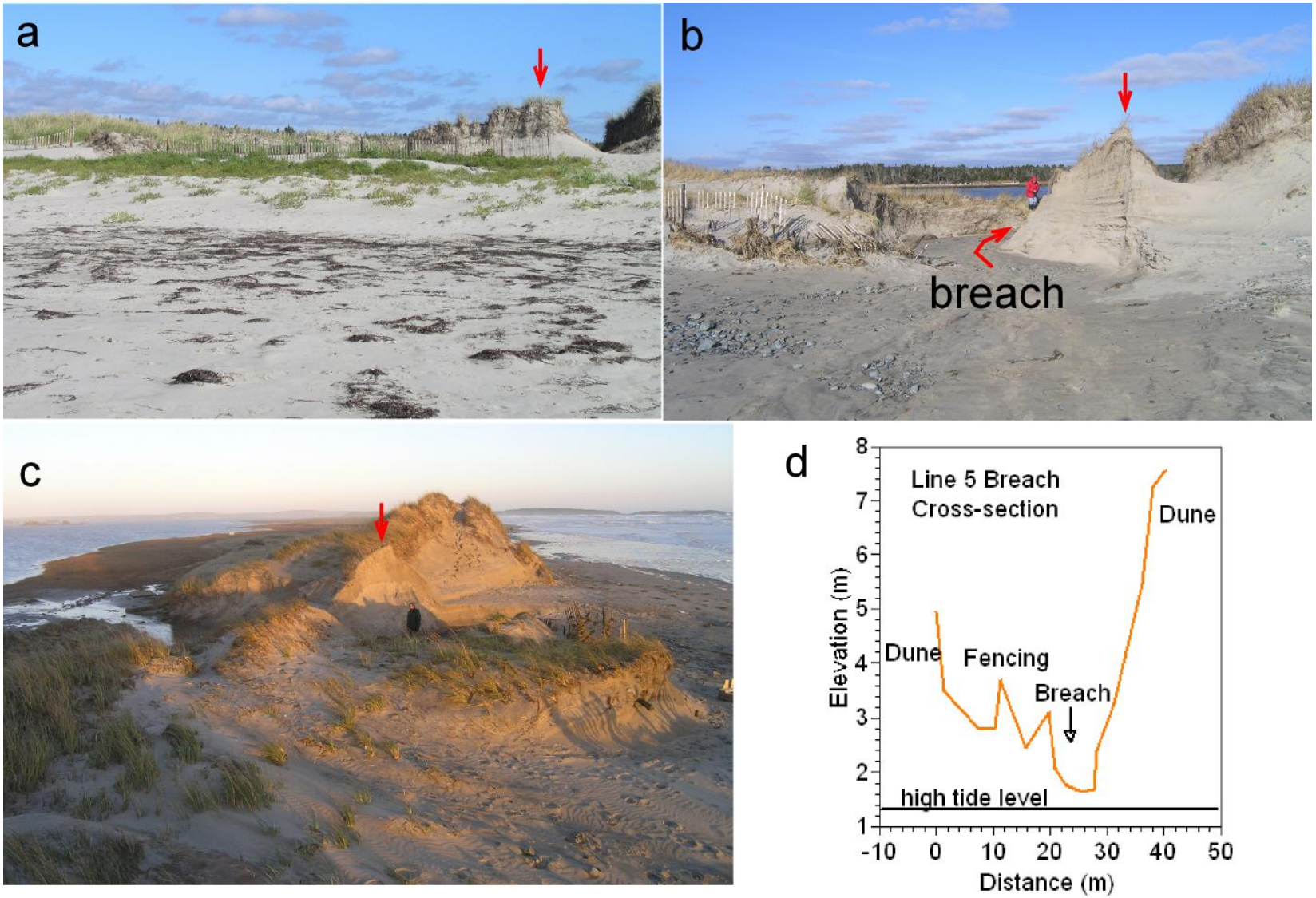


Figure 28. Views of beach at Line 5 (a) in September 2007 before Noel when a large foredune was developing seaward of fence lines (photo and (b) November 21, 2007 when our survey was completed after Noel (photo PB210782) (c) November 4, 2007 just after waves from Noel cut a channel through the dunes to the estuary behind (note water on left) (photo PB040320) and (d) longshore profile across the breach showing the extent of the breach relative to high tide level. Repetitive surveys across the dunes at Line 5 are illustrated in figure 29. Arrows mark the same location on each photo for reference.

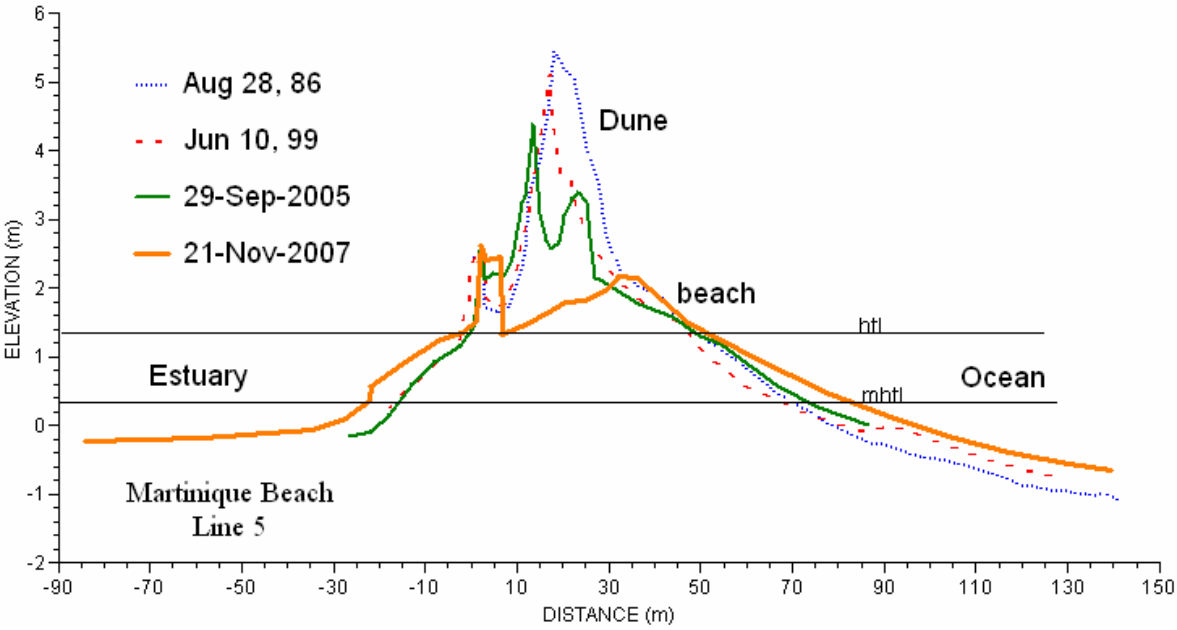


Figure 29. Repetitive cross-shore surveys at Line 5 where the blowout through the dune has progressed eastward since the mid 1980s leaving less and less backshore dune until it was cut by waves during Noel on Nov 3,4, 2007. The beach remains higher than the channel so only when waves extend above high tide level will water enter the breach and flow into the estuary.

SUMMARY- Martinique Beach - sand barrier with dunes

Waves overwashed roads and transported debris across all dunes <3.5 m (CGVD28) and overtopped dunes up to 5 m elevation. The greatest damage was to boardwalks and beach access stairs along the west end of the beach. Many of the larger pieces of boardwalk were transported to the east end of the beach. Waves widened several dune blowouts and cut a 10 m wide channel through the dunes to the backshore estuary at line 5. Waves lowered the beach slope, in places cutting it back by 8 m, trimmed the dune grass and scoured the base of the dunes downward by 1.2 m. The natural beach withstood the impacts of Noel however the narrowing and cutting through the dune in the vicinity of line 5 leaves that portion of beach more susceptible to large scale changes in future storms.

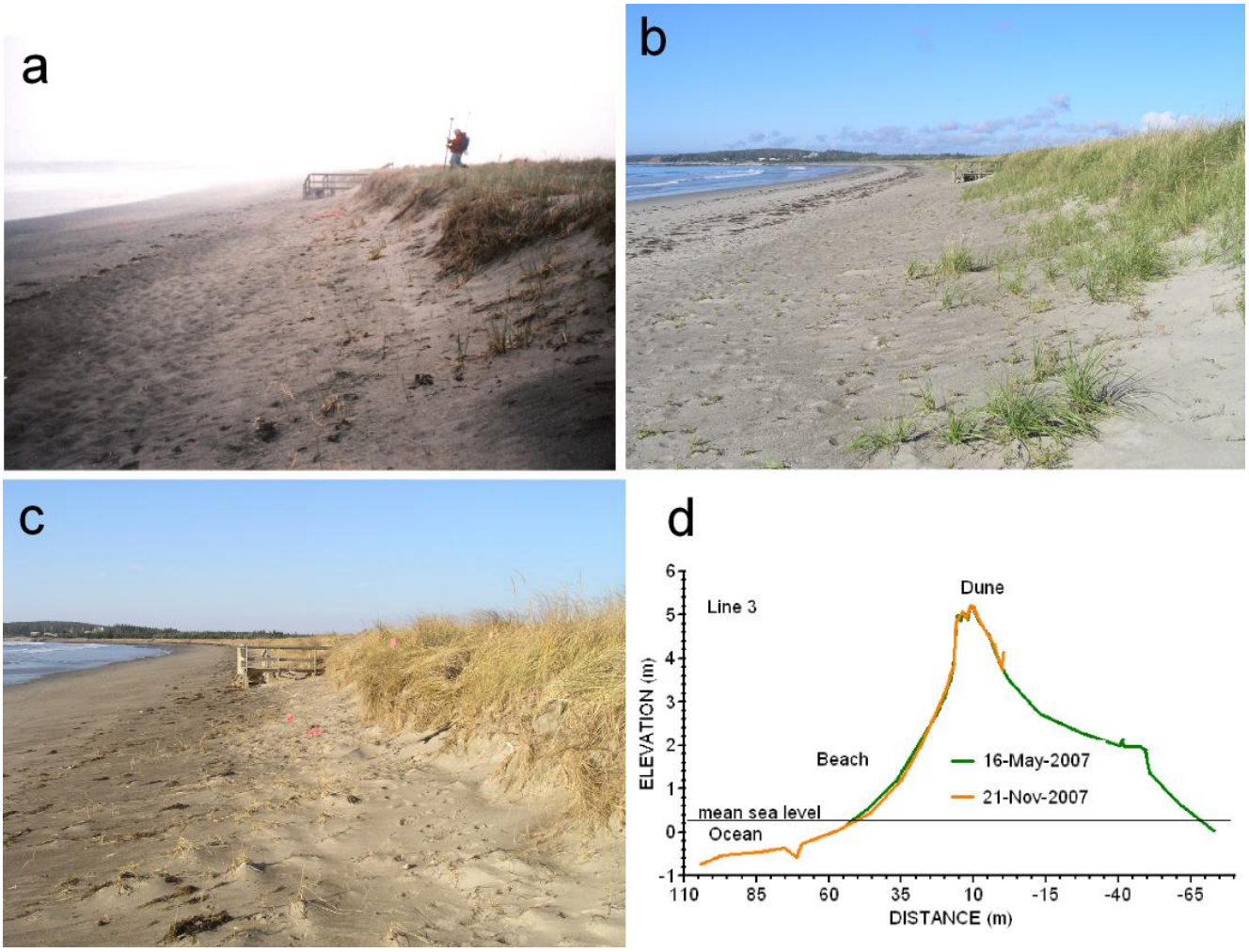


Figure 30. Views of the beach at Line 3 (a) on May 16, 2007 after a storm in April, (photo 3-02-2007) (b) in September 19 when the upper beach was built up by sand (photo P9190132) and c) Nov. 21 after Noel when the dunes were scoured by waves (photo PB210736). (d) repetitive surveys in May and Nov. show little net change in the beach but it does not reflect losses of sand accumulation between surveys in September 2007.

Figure 31. Views of Line 7 where sand was accumulating in (a) Sept. 2005 (photo P9290047) and (b) in May 2007 when a sand ramp existed (photo 17-02-2007) and (c) Nov. 21, 2007 when wind blown sand was rebuilding the base of the dune scoured by Noel on Nov. 4, 2007 (photo PB210792).

Crescent Beach, Lunenburg County

Crescent Beach is a 2 km long, 40 to 65m wide bayhead barrier/ tombolo in Green Bay. A paved road runs the length of the backshore connecting the mainland to George Island which is part of the Lahave Islands. The sand beach is separated from the tidal flats and salt marsh of Dublin Bay by sand dunes which rise in height from 2 m in the west to 6.8 m near the east end at L38b. A large wooden fence has existed between the beach and dunes since the 1930s.

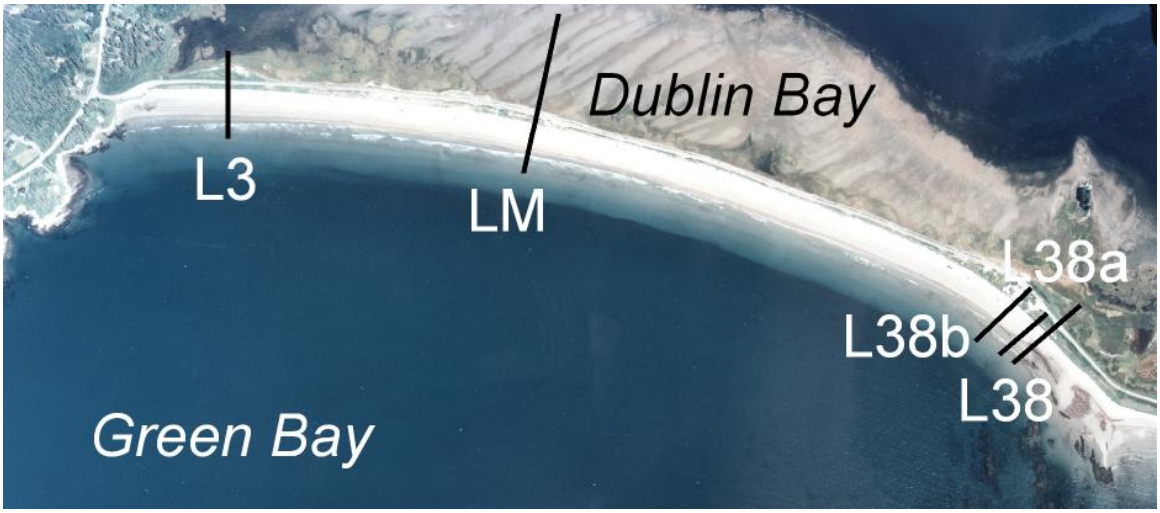


Figure 32 Location of cross-shore lines (L), e.g. L3, LM, L38b, surveyed on Nov. 8, 2007 to assess the impacts of Noel on Crescent Beach, Lunenburg County (92365-82, 7-Aug-92, Nova Scotia Municipal Affairs).

By Sunday morning Nov.4 waves had severely cut into and washed over low dunes along the western to middle portions of Crescent Beach. Photos by local residents Gordon Prince and Jim Sewell (http://www.crescentbeach.ca) showed the wooden fence severely damaged, power poles undermined and leaning (Fig. 4f) and sand piled in a number of places across the backshore highway. Along the eastern end of the beach storm impacts were less. They included some flooding across the highway from the beach access road, and wood debris tossed on the rock wall. By the time of our survey on November 8 and 9, all of the damaged power poles in the dunes had been replaced in roughly the same location as the original ones.

The extent of water flooding across the backshore highway is not known. From the position of debris lines we know waves reached 3.9 m elevation at Line M, 2.9 m at Line 38B and debris was tossed on top of the rock wall at line 38 which is 3.5 m elevation.. There is evidence that some water flowed over the dune crest at Line 3 which is 3.44 m elevation but it is believed most of the debris deposited in the Dublin Bay marsh was washed through adjacent low dune areas. Waves broke through the dunes where they were less than 3.4 m elevation (east of L3) depositing sand mainly across the road.

From photos it appeared sand, possibly as much as 0.5 m thick, extended across the road at the largest washover east of Line 3. Plows quickly cut a single lane through the sand for vehicles to travel along the road and subsequently plowed sand to both sides of the road. By November 8 some sand mounds remained along the side of the road but most sand was graded across the armour rock along the Dublin Bay side of the road and some sand was plowed toward the dunes. Yet the volume of sand observed across the backshore was small compared with the volume removed from the dunes during the storm. Where did all the sand go?

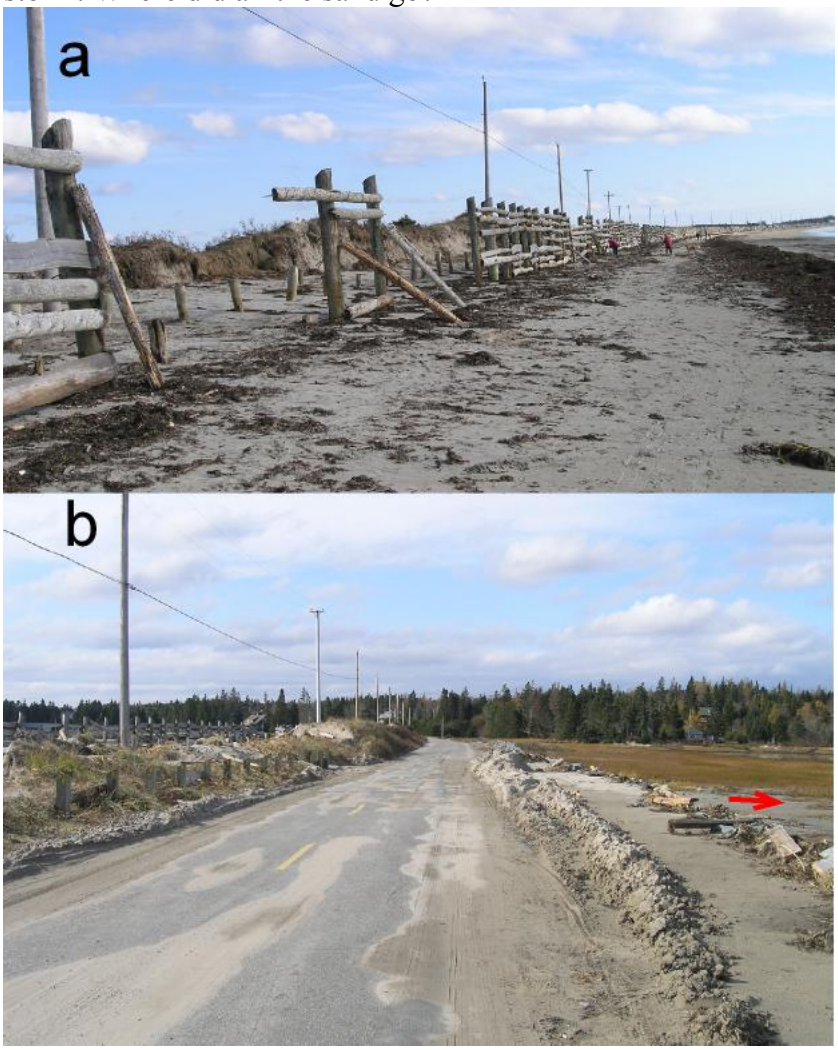


Figure 33. Site east of line 3 where waves damaged the wooden fence (a) and transported sand (b) across the highway into Dublin Bay (arrow). (photos PB090639, PB090648, R. Taylor Nov 9, 2007).

Changes along Crescent Beach have been monitored by the Geological Survey of Canada intermittently since the late 1970s, at as many as five locations along the beach. To assess the physical impacts of Noel, three cross-shore lines were surveyed and compared with previous surveys at specific locations. Unfortunately, the last detailed surveys were completed in July 2003 which was just before Hurricane Juan. Impacts to the beach by Juan were compiled from photographs taken by local residents J. Comilli, B. Raymond and G. Prince and during a brief visit to the site but cross-shore beach lines were never completed as planned. The shoreline monitoring program was cancelled by the

Geological Survey in April 2006 but the same residents continued to assist us by collecting photographs of beach changes. Fortunately on October 7, 2007 just prior to Noel, the beach was re-photographed and brief observations of beach and dune conditions were completed. It is mostly these photos that are used to illustrate the impacts of post tropical storm "Noel".

By October 2007 sand had accumulated along the upper beach and small dunes were building intermittently along the seaward edge of the wooden fence. Back of the wooden fence, the dunes nearly extended to the wooden fence but were scarped.

Figure 34. By early October 2007 sand had accumulated along parts of the seaward side of the wooden fence forming a small foredune similar to what had occurred in September 2003 just prior to Hurricane Juan (photo PA070198, R. Taylor)

On November 9 detailed surveys were completed across three beach lines 3, M and 38B (Fig. 32). The surveys were extended from the tidal flats in Dublin Bay to chest water depth in Green Bay. A wooden fence and a backshore dune existed at all three locations. Line 3 was located at the west end of the beach, just west of one of the largest wave overwash occurences during Noel; Line M was just west of the older armour rock fringing the central beach, and line 38B was at the highest dune just west of a rock wall fringing the eastern end of the beach.

Graphs and photographs illustrate the range of net changes observed across each line. They illustrate conditions in 2003 when lots of sand had accumulated across the upper beach and the dunes were healthy and another time when backshore dunes and sand accumulation was at their worst. Since 2003 the greatest loss of sediment across the intertidal zone was at line 3 where it was lowered by 0.5 m (Table 2), the lowest recorded since 1981. At line M the intertidal was only lowered by 0.1 to 0.3 m and at Line 38B

the intertidal indicated a net build-up by 0.3m since 2000 (Table 2). The beach had been lowered by waves at the east end of the beach during Noel. The net increase in sand accumulation is attributed to a larger long term build-up of sand at that end of the beach which offset the losses during Noel. Across the upper beach, seaward of the fence, the loss of sand was 0.4 to 0.5 m at all three lines and landward of the fence the loss of sand varied from 0.4 to 1.2 m in thickness and the dune was cut back by as much as 5.7 m (Table 2). Dune cuts adjacent to the survey lines were as much as 2-3 m more and the cuts extended nearly to the road, east of line 3. Since 2003 the crest or highest portion of backshore dune remained stable or increased by 0.2 m in elevation as the vegetation cover had improved and trapped sediment. Little net change was observed landward of the dunes and within Dublin Bay except for the road work completed. At Line M the shoulder of the road had been widened by 6 m since 2003 (Fig. 35e).

Before Hurricane Juan in September 2003, sand was building with variable cover of vegetation landward of the crib work from 2001 and dunes had built seaward of the fence. The lack of significant wave damage from Juan was attributed to the good condition of the dunes yet we see in Noel a similar sand accumulation prior to the storm and much greater damage. It is more obvious now that the duration as well as the greater intensity of the wave field controlled the magnitude of dune retreat and it would have been much greater if sand accumulations were not present across the upper beach and backshore. For example, during Juan the largest waves did not extend much farther west than Mahone Bay, whereas during Noel they extended, significantly farther west, into the Bay of Fundy.

Three cross-shore surveys of Crescent Beach were not sufficient to provide answers to where all the sand eroded from the dunes was deposited. Our surveys did not cross the most damaged parts of the beach. Also the surveys are too far apart both in distance and in time since the last survey. The original survey lines were chosen as sites for measuring the magnitude of representative changes at both ends and the central part of the beach. They were chosen well for that purpose. Surveys in November 2007 show the greatest beach changes were at the west and central parts of the beach and least at the east end which is similar to what has been observed after other large storms. The changes suggest some sand may have been moved toward the eastern end of the beach but the changes surveyed represent a four year time span. Visual observations and photographs from residents indicate a significant proportion of sand eroded from a few specific dune areas was deposited on the highway back of the beach and a smaller amount of debris and sand reached Dublin Bay. Along most of the eroded dune, waves did not overwash dunes and the sand did not reach the highway. It is concluded that most of the sand eroded from the dunes was swept downslope and just offshore and as in the past it has the potential to be moved back upslope given the right wave conditions.

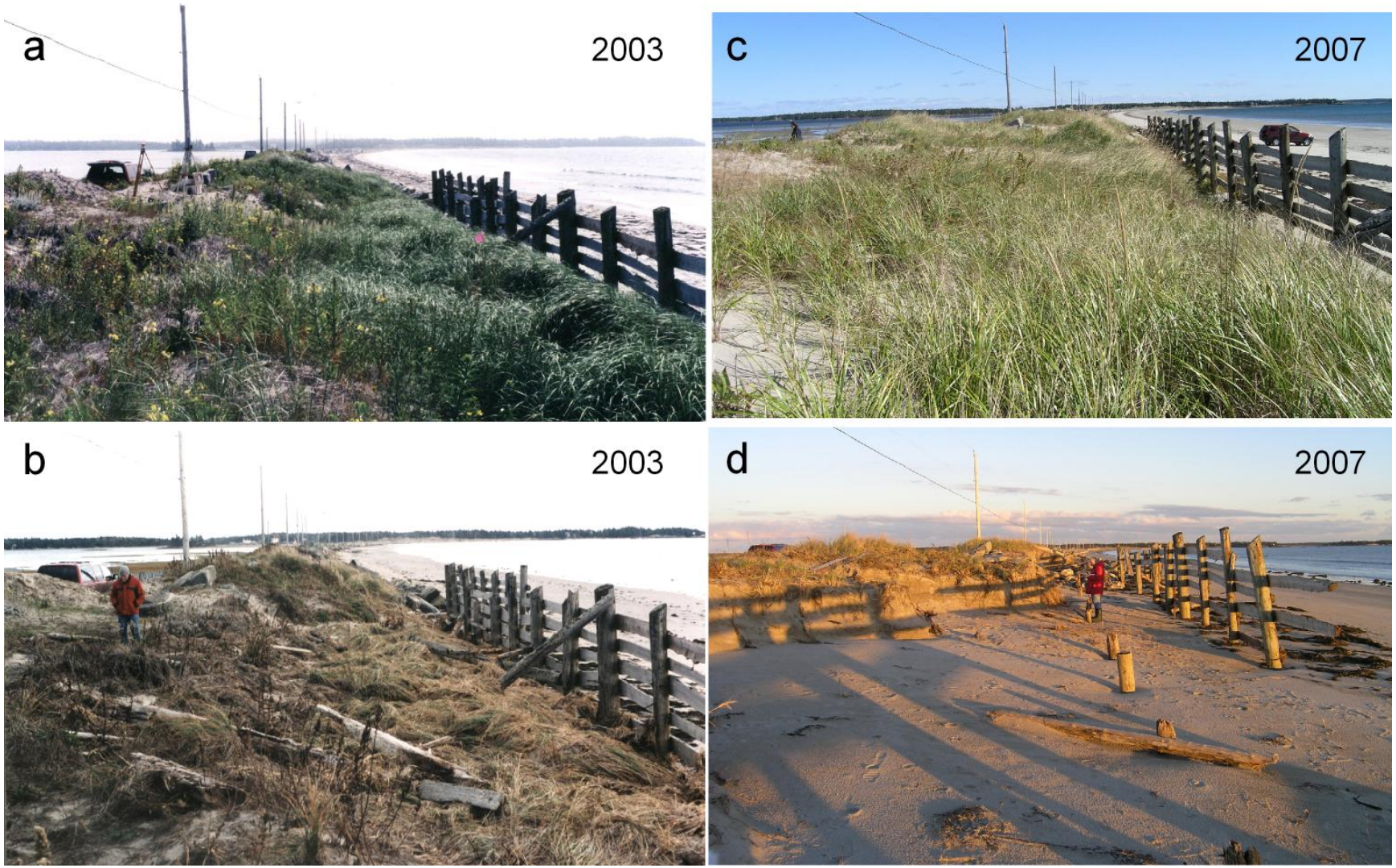
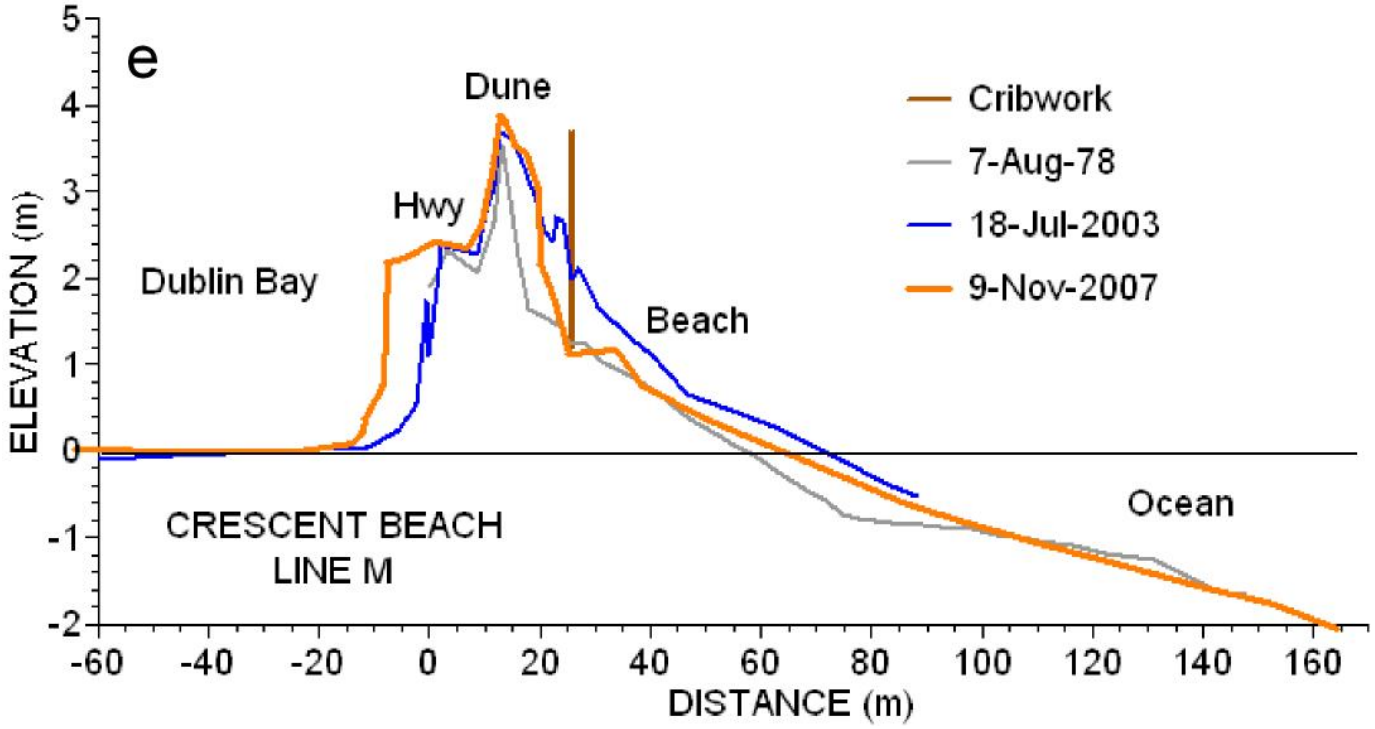


Figure 35. Views of Line M Crescent Beach (a, b) before and after Hurricane Juan in 2003 (photos 4-05-2003 July 18 and 23a-19-2003, Oct. 24) and (c, d) before and after Noel in 2007 (photos PA070195 Oct. 7 and PB080587 Nov. 8) illustrating the increased destruction and wave scouring during Noel when large waves struck the beach for a longer time period than during Juan.

Figure 35 (e) select surveys of the beach showing the size of the dunes before Hurricane Juan and after Noel. Despite the destruction to the dunes in 2007 it was not as bad as it was in 1978 when it was first surveyed.



A comparison of photos and surveys from 2007 suggest the beach has been scoured down and deteriorated to conditions observed in the late 1970s to early 1980s and in the late 1990s (1997-1998). Phases of dune progradation and erosion lasting 5-6 years at intervals of 14 to 18 years with episodic destruction during storms have been observed in the past. The dunes were best developed in 1992 and in 2003. There is no reason that they could not do it again since there was little net loss of sand from the beach system. By November 22, 2007 an estimated 10,000 tons of armour stone was added between the fence and backshore dunes which will severely alter the natural cycle of backshore beach changes. Although no guarantee could be made that the beach would not be struck by another storm in quick succession, the addition of armour rock was completed before a full assessment of the situation was completed. The addition of armour rock will not prevent the deposition of debris across the road in future storms, and in fact it could enhance it with the addition of more rock and less sand. Also the introduction of armour rock will not eliminate the need for road maintenance after storms because water can flow through rock easier than thick sand dune. It remains to see if the sand can accumulate and bury the rocks.

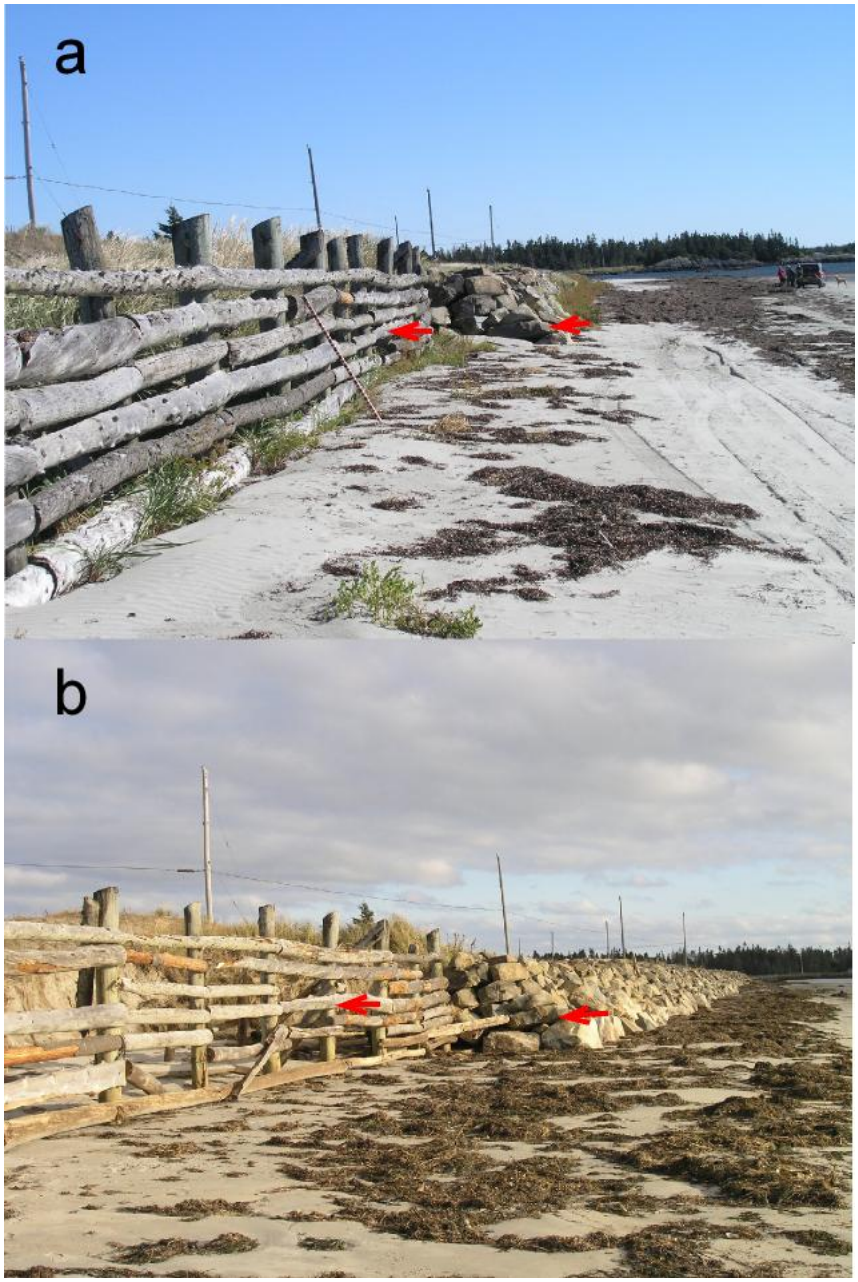


Figure 36. View of the fence and rock wall at the east end of Crescent Beach at Line 38 on (a) Oct. 7, 2007 and (b) Nov 9, 2007 showing a similar depth of wave scouring by waves during Noel at the two interfaces. Arrows mark the same location on each photo. The survey pole against the fence in (a) is 1.54 m long. (photo PA70205 and PB090685, R. Taylor)

Table 2. Changes in beach conditions and amount of sand accumulation at Crescent Beach after Post-tropical Storm Noel, November 3-4, 2007.

Line (beach section)	Lower Beach (vertical)	Upper Beach (vertical)	Backshore (Lwd of fence)	Dune Retreat	Dune Crest Elevation
3 (west)	-0.5 m	-0.4 m	-1.0 m	4.0 m	-0.15
M (central)	-0.1 to-0.3 m	-0.5 m	-0.6 to-1.2 m	5.7 m	+0.16
38B (east)	+0.3 m	-0.4 m	-0.4 m	2.9 m	no data

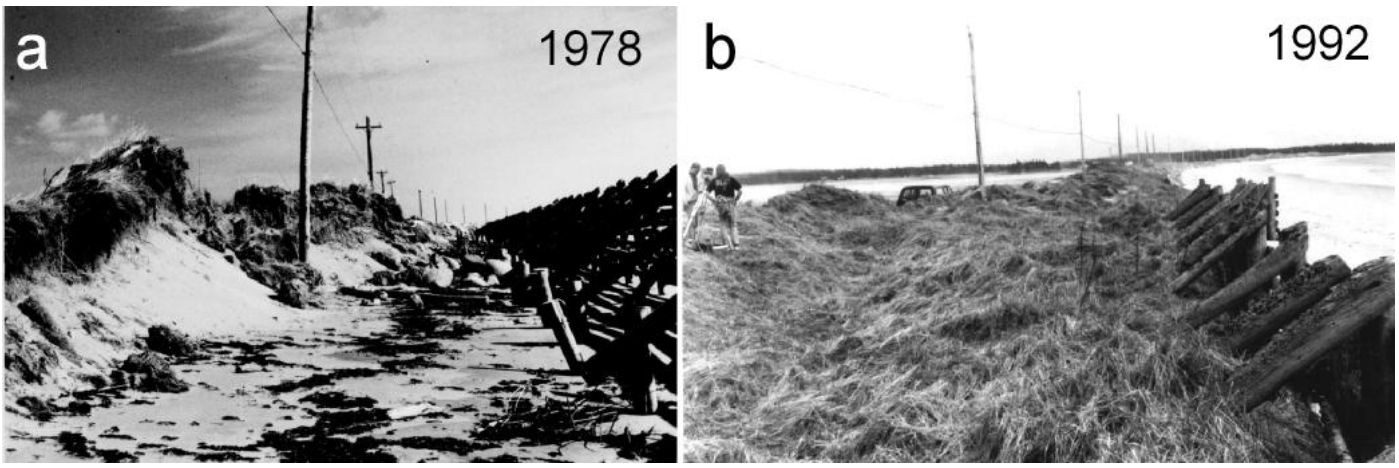


Figure 37. Views of Crescent Beach at Line M showing its most scoured condition in 1978 (photo by H. Munroe) and widest dunes in 1992, (photo by R. Taylor) illustrating the cyclic changes that can occur on this beach.

SUMMARY- Crescent Beach - sand barrier with dunes

Increased duration of larger waves caused more damage to the dunes, and wooden fence protecting them, than during Hurricane Juan. Waves reached at least 3.9 m (CGVD28). In the west, waves cut the dunes landward to within 1 m of their crest adjacent to the backshore road, and undermined power poles. Dune erosion was a maximum of 5.7 m at the survey lines and possibly as much as 7 m elsewhere. The west end of the beach was scoured to its lowest level since 1981 while the eastern end of Crescent Beach was 0.3 m higher than our previous survey in 2003. The volume of sediment eroded from the dunes can not be accounted for onshore; therefore, most sand was carried offshore and has the potential to be moved back onshore given the right wave conditions. Dunes along the western to central beach appeared destroyed following Noel. Previous surveys showed they were not as badly cut as in 1978 and the dunes have naturally rebuilt themselves at least twice since 1978.

Hirtles Beach, Lunenburg County

Hirtles Beach is a 2.6 km long mixed sediment beach backed by a series of ponds and drumlins at the head of Hartling Bay (Fig. 38). In the past when water levels rose in Hirtles Pond, water was directed toward Romkey Pond and emptied through a tidal channel (Fig. 38 circle) which frequently linked Romkey Pond to the ocean.

Figure 38. Aerial view of Hirtles Beach at the head of Hartling Bay showing the location of survey line L1, the new channel cut through the beach during Noel (arrow) and site of the tidal channel (circle) that flows into Romkey Pond (air photo 92354-143; July31,1992).

Waves from Noel overwashed the beach ripping away the backshore boardwalk between Hirtles and Romkey Ponds, leaving only the more secured parts leading from the parking area to the beach. Most pieces of boardwalk were floated into the backshore to elevations of 2.0 to 2.7 m, as much as 67 m landward of their original location. The highest wood and grass debris line was at 2.9 to 3.1 m elevation along the backshore upland slope. Waves from Hurricane Juan had had a similar impact on the boardwalk in 2003. After Juan the boardwalk was rebuilt back of the dune in roughly the same location.

Figure 39. Extent of wave overwash and deposition of coarse clasts between Hirtles and Romkey ponds as a consequence of Post-tropical Storm Noel, Nov. 4, 2007. Beach survey line 1 extends from the parking lot, at left side of footbridge, past where the surveyor is standing. (PB080551, Nov 8, 2007, R. Taylor)

The most dramatic change to Hirtles Beach, Hartling Bay was the cut (Fig. 38, 40 red arrow) through the barrier beach fronting Hirtles Pond which became drained following the breach. Local residents do not remember a channel ever joining the ocean and this pond. The waves cut a 35 m wide channel 4 m deep through the barrier beach (Fig. 41). Base level of the channel was -0.75 m geodetic which is at or below low tide level. After Noel the top of the barrier beach had an elevation of 3.1 to 3.4 m.

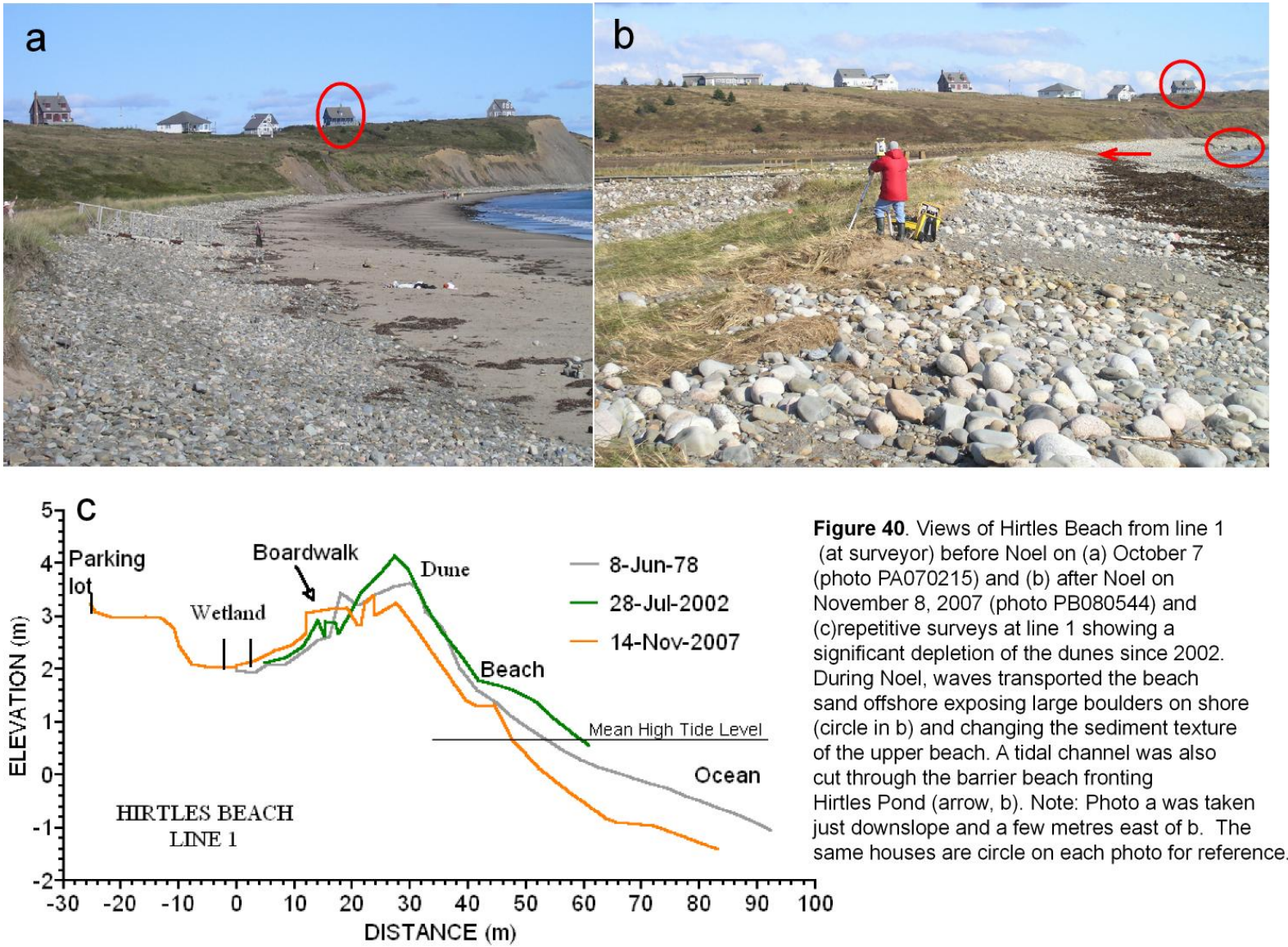


Figure 40. Views of Hirtles Beach from line 1 (at surveyor) before Noel on (a) October 7 (photo PA070215) and (b) after Noel on November 8, 2007 (photo PB080544) and (c)repetitive surveys at line 1 showing a significant depletion of the dunes since 2002. During Noel, waves transported the beach sand offshore exposing large boulders on shore (circle in b) and changing the sediment texture of the upper beach. A tidal channel was also cut through the barrier beach fronting Hirtles Pond (arrow, b). Note: Photo a was taken just downslope and a few metres east of b. The same houses are circle on each photo for reference.

A number of wave washover channels had lowered the crest; in one case to 1.6 m elevation but did not cut completely through the barrier (Fig. 41b). Before the channel was cut, water level in Hirtles Pond existed at 1.5 m elevation and after breaching, the pond became tidal. High tide level on November 14 was at 1.1 m and water level at the time of our survey which was about an hour before low tide was at 0 m elevation. The vertical displacement of water was close to mean tidal range of 1.5m for the area (Fig. 42). On November 14 there were actually two small channels within the breach separated by a 0.3 m high deposit of sand. Although a low channel remained, water levels in Hirtles Pond had been restored to near pre-Noel levels by the end of February 2008 (pers. com. local resident, Tony Congdon) because of natural infilling of sediment in the cut.

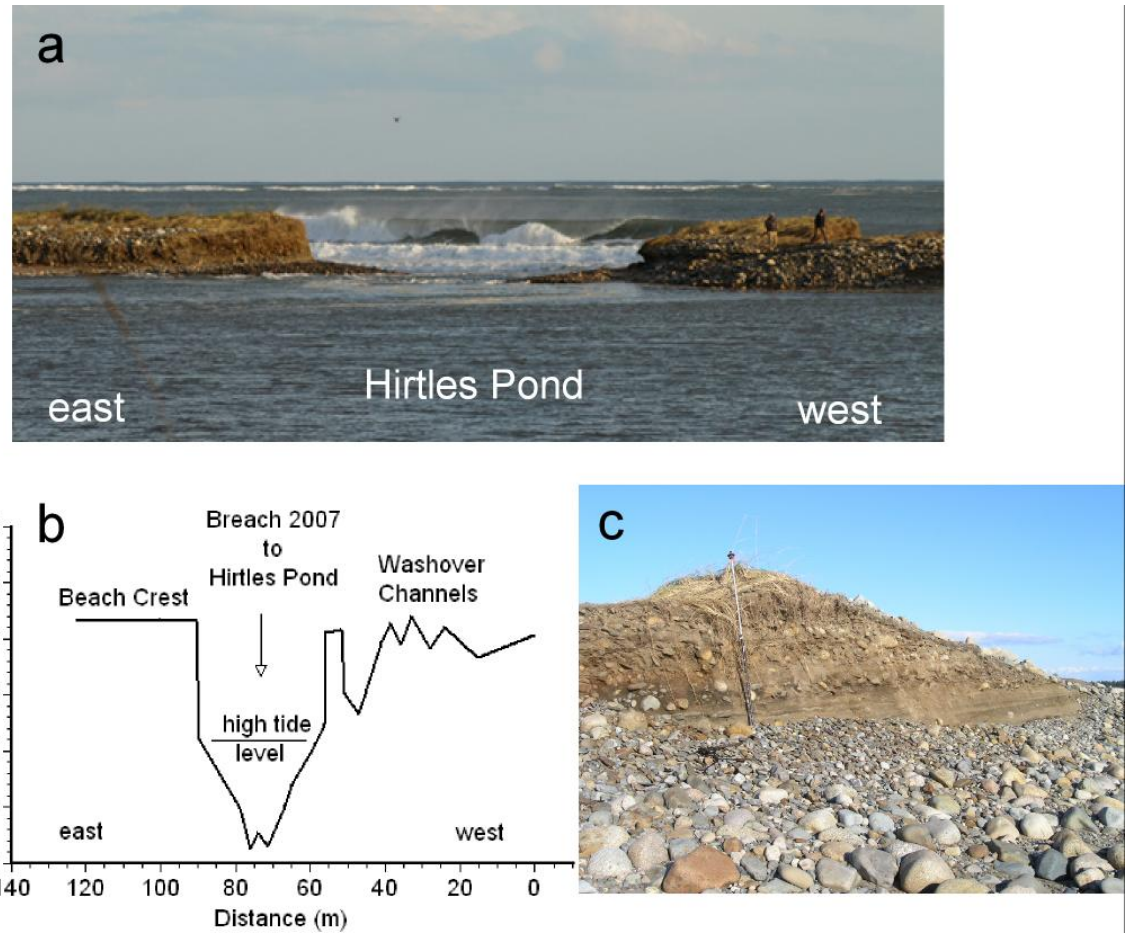


Figure 41. (a) View (Nov. 5,2007) looking seaward across Hirtles Pond at the new tidal channel cut through the barrier beach during Noel (b) a cross-sectional profile of the channel surveyed on Nov. 8, 2007 and (c) a close-up of the barrier beach stratigraphy on the east side of the channel. Scale-the pole leaning against the bank is 2m long. (photos (a) D. Mercer; (c) PB080563, Nov. 8, 2007, R.Taylor).

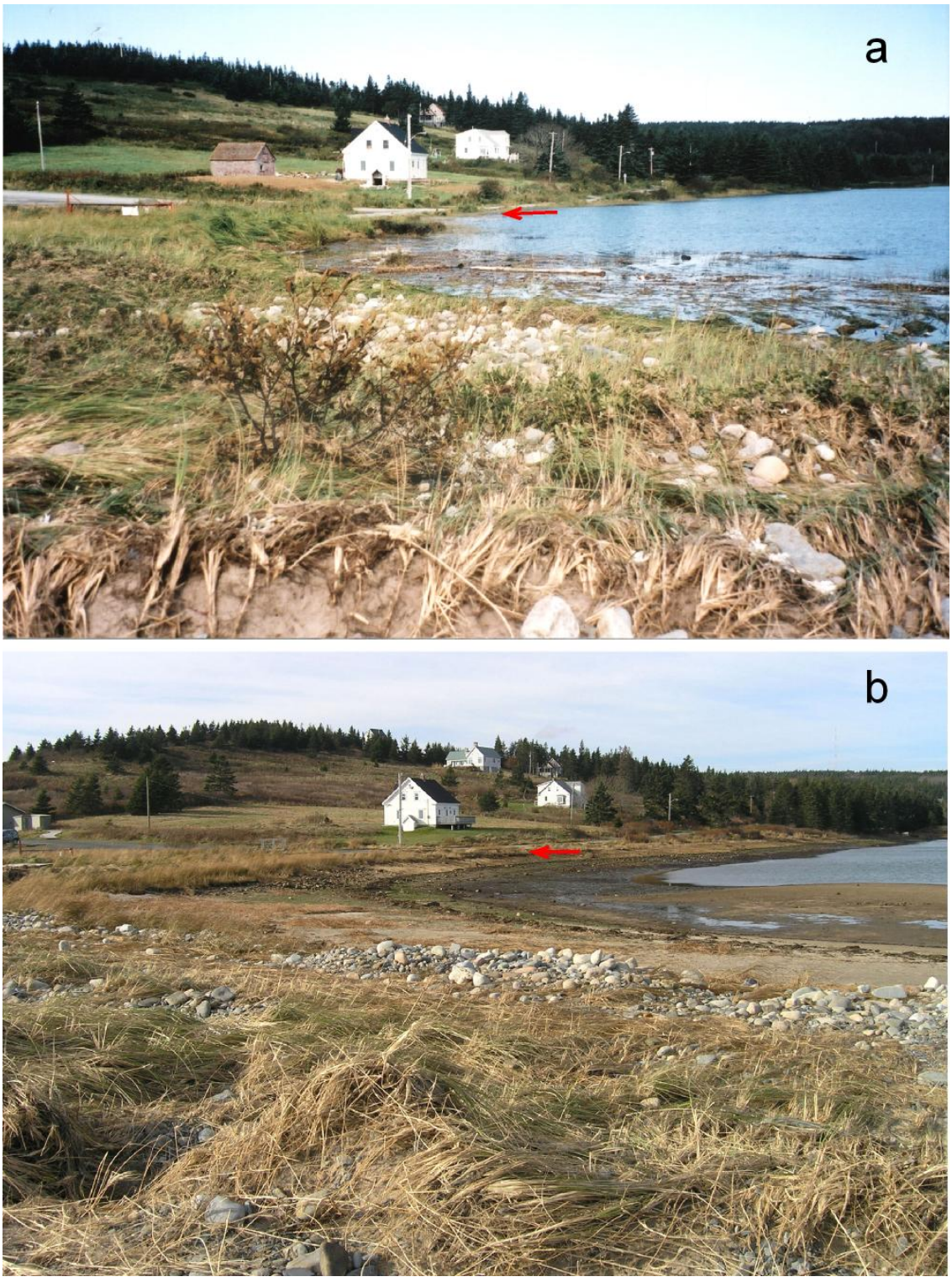


Figure 42. Comparison of water levels in Hirtles Pond (a) before and (b) after a channel was cut through the barrier beach to the pond during Post-tropical Storm Noel Nov. 4, 2007. Arrows in both photos mark the water level before drainage. Water levels are now tidal and the vertical difference in water level in the two photos is 1.1 m (photo 14-29-2003 by J. Comolli and PB140711 by R. Taylor).

A channel was also cut through the beach at Romkey Pond where it has frequently done in the past. This cut was already partially infilled with sand by November 14 and people could walk across it at or near low tide stage. Also, waves washed over the barrier beach into the small pond at the far eastern end of Hartling Bay but did not cut a channel through the barrier beach.

A significant reduction in beach width and height was also observed at our beach monitoring site which exits just seaward of the main beach parking area. Since our previous survey of the beach was completed in July 2002 before Hurricane Juan, it is difficult to differentiate the impacts of Noel from other previous storms including Hurricane Juan. Net beach change over the five years included: a 10.5 m landward retreat of the beach at mean sea level and a near complete loss of dune. The dune was reduced from 10 m wide in 2002 to less than 2 m in 2007. The dune crest retreated 3.8 m landward and was lowered from 4.1 m to 3.4 m elevation by Nov. 2007 which makes it much more vulnerable to frequent wave overwashing. From photos it is apparent that there is still sufficient sand just offshore to rebuild the beach slope but there has not been sufficient time or sediment to rebuild the dunes and backshore. As a consequence Hirtles Beach has accelerated its natural landward migration since 2002.

SUMMARY- Hirtles Beach -mixed sand and gravel barrier with dunes

Since our last survey in 2002 the dune had been reduced from 10 m to less than 2 m wide and its crest was reduced from 4.1 to 3.4 m elevation (CGVD28). As a consequence waves easily washed over the beach, deposited large amounts of cobble across the backshore and ripped out the boardwalk which was floated 67 m across a low wetland to an elevation of 2.7 m. The highest potential floodline, marked by wood and grass debris, was 3.1 m elevation (CGVD28). The beach was stripped of its sand. The net landward beach retreat since 2002 was 10.5 m. The most dramatic change during Noel was the cutting of a channel through the barrier beach to Hirtles Pond from the ocean. Hirtles Pond was drained and became tidal. This was the first time residents ever remember a channel to Hirtles Pond, even though channels are frequently cut into nearby Romkey Pond. Changes at Hirtles Beach following Noel were natural, but somewhat larger compared with the longer term sequence of landward beach migration.

Cherry Hill Beach, Lunenburg County

This mixed sand and gravel barrier beach is located on the east side of Medway Harbour. The beach has been rapidly breaking down since its mid-section was extensively overwashed by waves during Hurricane Juan in 2003. On Nov. 9, 2007 field surveys were restricted to the eastern end of Cherry Hill Beach where the beach crest was surveyed as well as cross-shore line L1.

During Noel, water overwashed the dunes where the crest was 4.0 m or less in elevation and where it was less than 3m large amounts of pebble -cobble and driftwood debris were carried as much as 75 m inland from the dune crest. Only a short section of beach remained where the dune crest was 4.5 m or higher which prevented wave overwash. Two deep washover channels 12 and 6 m wide were cut through the dune to the vehicle parking area. The backshore dune was cut down just over 1 m to an elevation of 2.3 and 2.5 m.

Figure 43. 1992 aerial photograph of Cherry Hill Beach with the location of cross-shore survey line 1 and vehicle parking area. Since 2003 the water body between the Cooper Island and line 1 has been episodically infilled by sediment. During Noel the backshore flats (yellow area) nearly reached the mainland shore just east of Cooper Island .

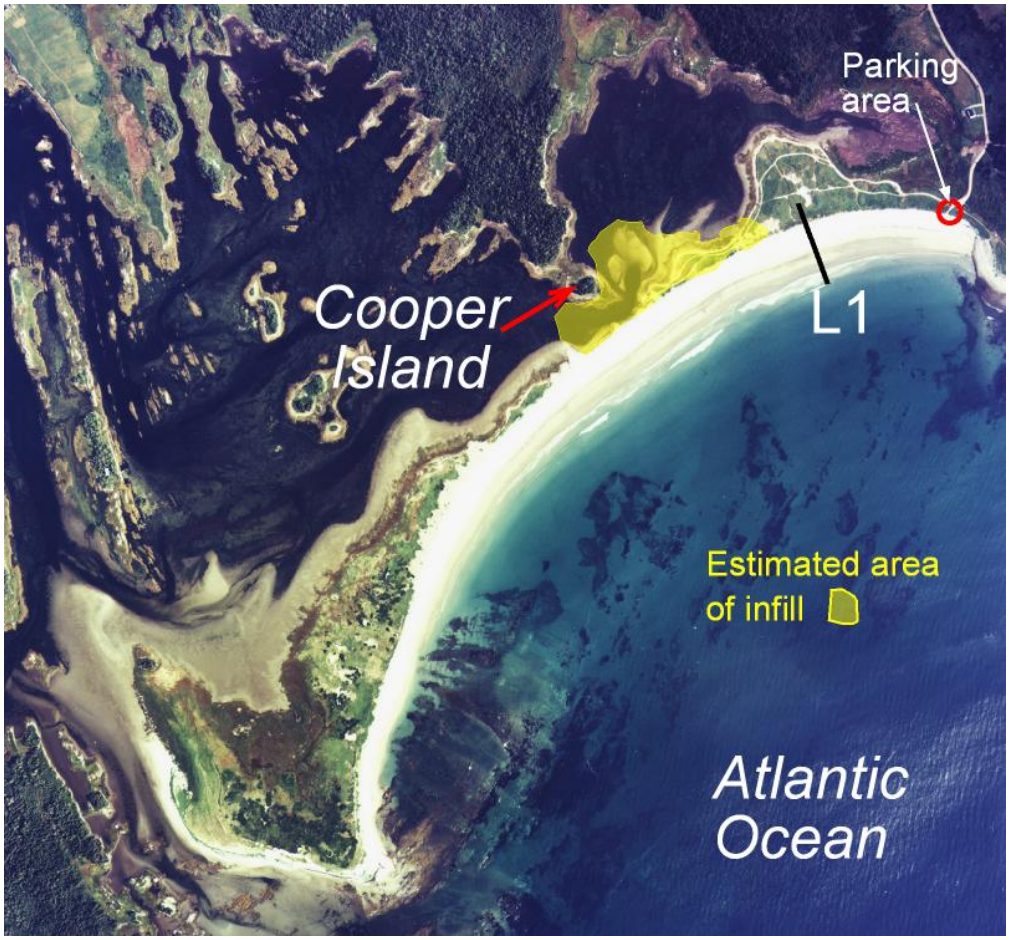


Figure 44. Waves from Noel (a) rolled back the seaward edge of the dune as cobble was pushed higher upslope and (b) transported flotsam and pebble cobble material as much as 75 m into the backshore as shown just east of cross - shore line 1 (marked by pink flags and t-bar circled) . (photos PB090615 and PB090607, Nov. 9, R. Taylor).

b

Since our last longshore crest survey in 2003 the dune crest has migrated progressively farther landward toward the west. The maximum recorded retreat was 20.4 m landward at the western end of our 2007 survey where the dune was essentially erased being lowered by as much as 1.4 m and buried by pebble cobble. After Hurricane Juan the central part of Cherry Hill Beach was extensively overwashed and the lagoon shoreline was pushed farther landward. It is believed the lagoon shoreline was pushed farther landward during Noel particularly just east of Cooper Island where a lobe of sand nearly extends to the mainland. Furthermore and the zone of extensive wave overwash has been extended 140 m farther eastward approaching the position of our cross-shore survey line. Despite increased sediment deposition into the back lagoon the connection remains open back of Cooper Island between the east and west lagoons.

In contrast, at the far eastern end of Cherry Hill Beach the crest had prograded farther seaward since 2003 but in 2003 the survey followed the duneline and in 2007 it followed the highest beach ridge which was a similar elevation or slightly higher than the dune behind.

At our cross-shore line (Line 1) the most recent survey before Noel was in October 2003 after Hurricane Juan. Since then the beach has maintained its crest elevation through sediment accumulation as it migrated 6.9 m landward. At high tide level the beach has retreated 9.6 m landward and sand accumulation against the beach slope was the lowest measured in 29 years. The highest sand level was recorded in May 1992 when it was at 1.9 -2.1 m and lowest at 0.8 -0.9 m following Hurricane Juan and Post-tropical Storm Noel. Maximum vertical fluctuations in sand levels varied from 0.95 m across the subtidal area and as much as 1.3 m across the intertidal zone. Dune retreat as a result of Noel was only measured at the provincial survey marker just east of our cross shore line. On October 7, 2007 the marker was at the edge of the duneline and on November 8 the duneline was 0.64m landward of the marker. Present dune elevation and position are listed in Table 1 to illustrate the longer term changes since the dune was at its maximum size in 1997.

Table 3 Changes in dune crest elevation and position since its maximum growth in 1997 as measured at cross-shore survey line 1.

Date	**Dune Crest Elevation (m)**	**Dune Crest Retreat (m)***
19-May-1997	4.81	
26-May-2001	4.37	-1.1
18-July- 2003	3.88	-0.3
24-Oct-2003	3.55	-0.2
9-Nov-2007	3.53	-6.9

*Position is relative to the 1997 crest position

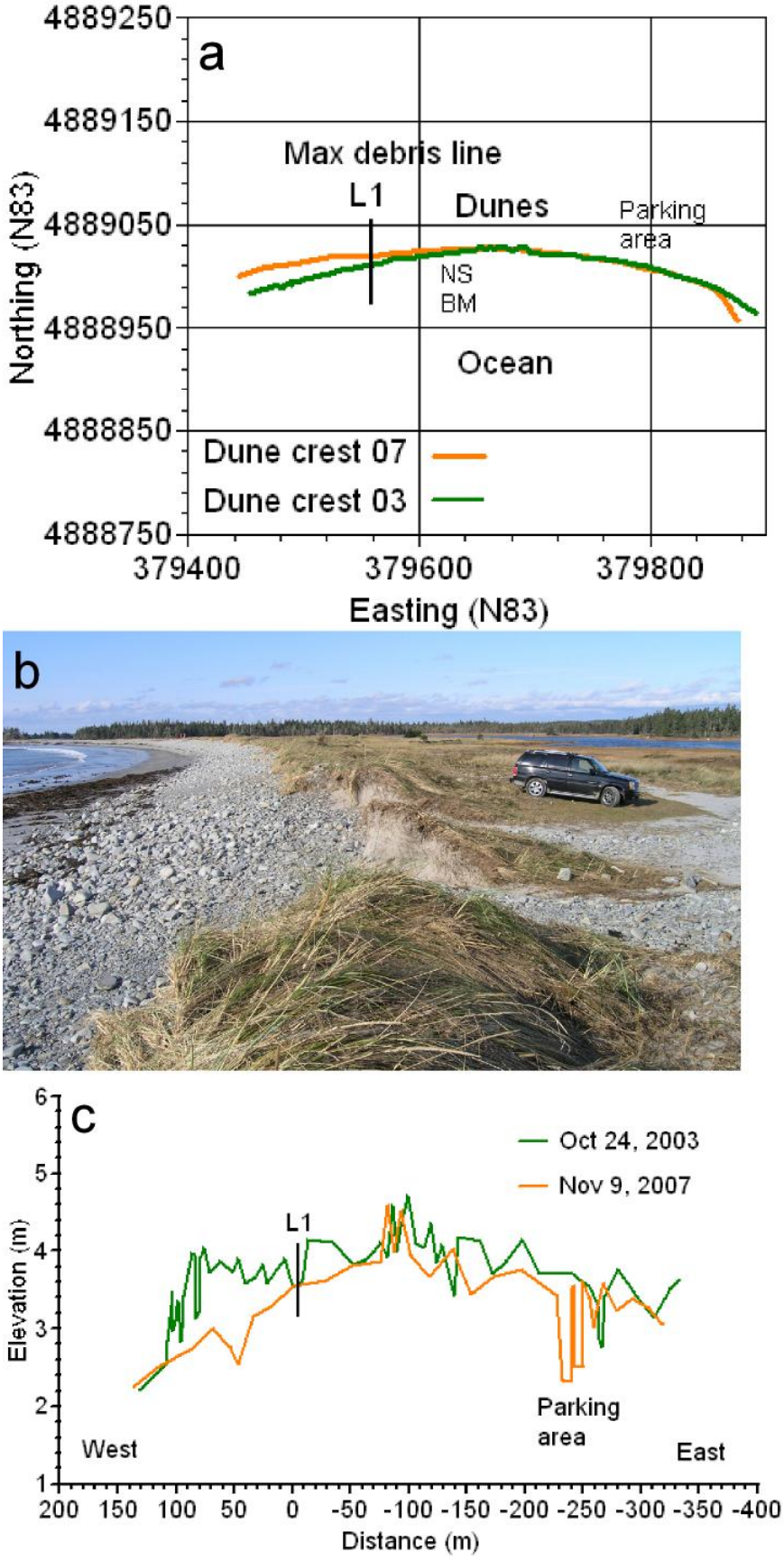


Figure 45. View and graphs of east end of Cherry Hill Beach showing changes to primary dune crest as a consequence of wave attack during Noel, Nov. 4, 2007. (a) positional changes in the dune crest since 2003 (following Hurricane Juan) and after Noel; largest landward migration was at the west end of the survey whereas at the east end beach ridges built seaward of the dune. (b) two channels cut through the dune at the main parking area Location of parking area is shown on graphics a and c. (photo PB090612, Nov. 9, 2007, R. Taylor) and (c) longshore profile of dune crest showing the areas of greatest lowering and scouring and the small area that remained intact- To better understand this profile pretend you are standing offshore looking back at the beach looking at the highest part of the beach which consists of many low areas cut by waves.

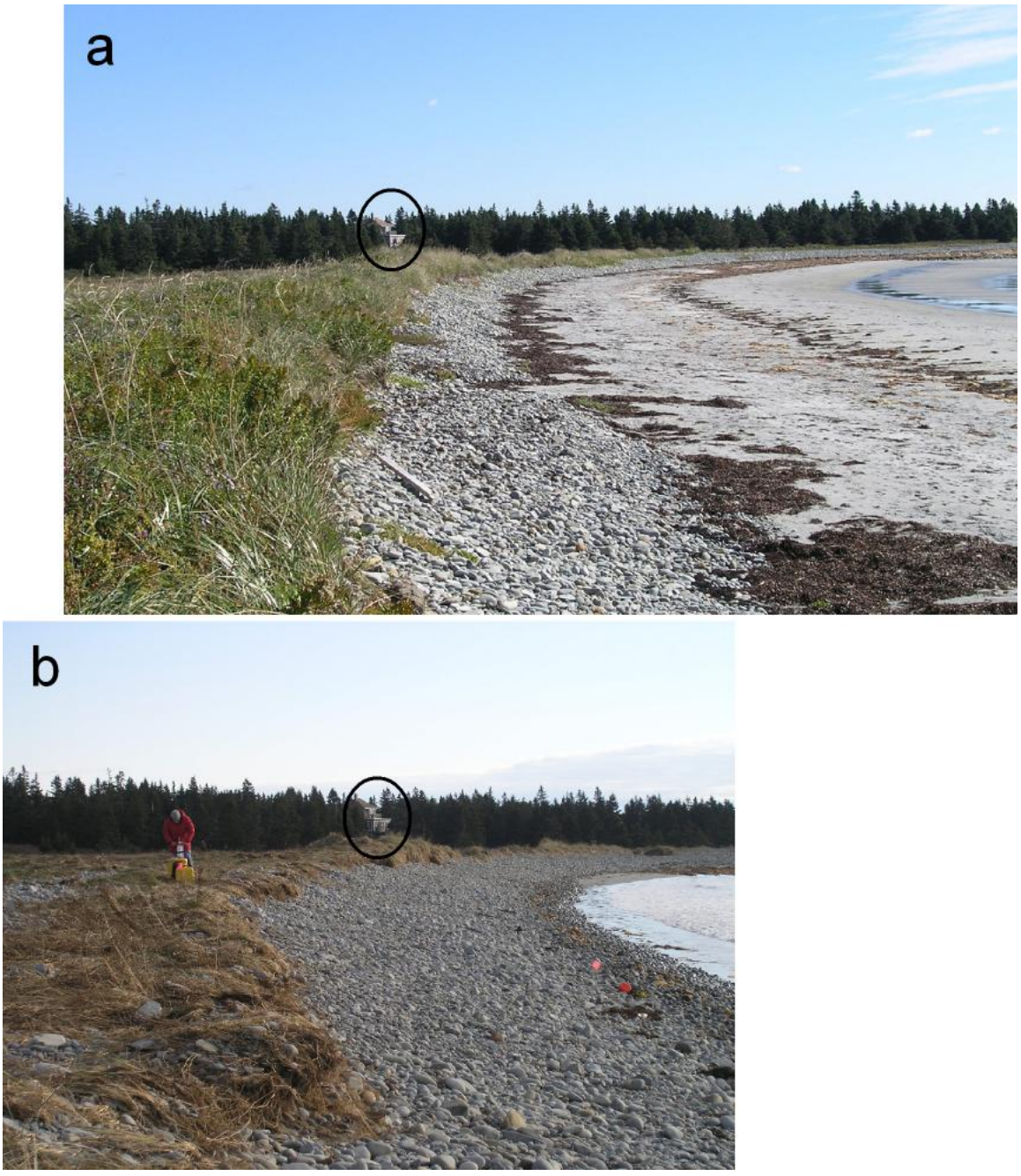


Figure 46. Views looking east of cross-shore survey line 1 (a) on October 7, 2007 just before Noel and (b) on Nov 9, 2007 just after Noel (photos PA070160 and PB090599, R. Taylor).

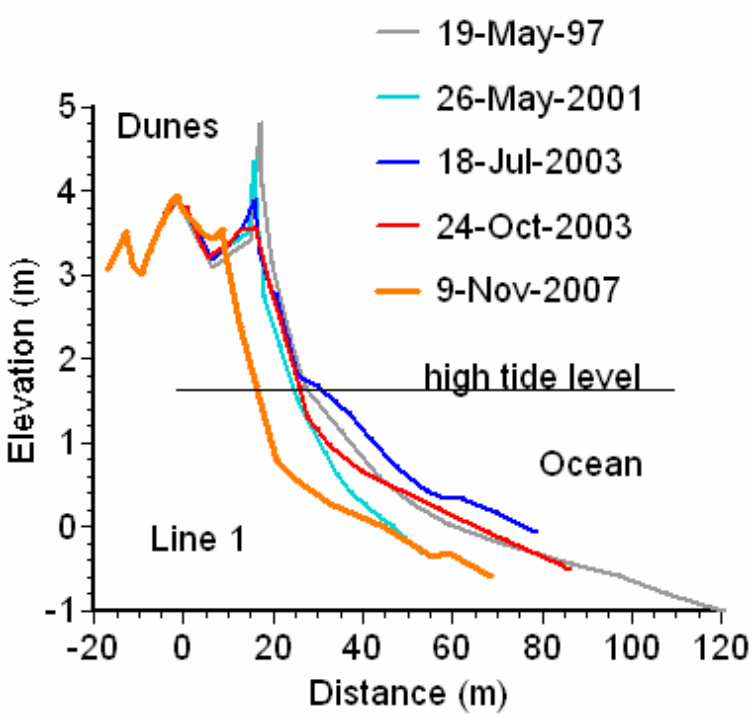


Figure 47. Repetitive surveys of line 1 showing nearly 10 m of landward retreat at high tide level since 1997. Since 1997 the primary dune was lowered in elevation by 1.3 m and it retreated by 8.5 m (Table 3). Photos of Line 1 before and after Noel are shown in Figure 46.

SUMMARY- Cherry Hill Beach -mixed sand and gravel barrier with dunes

Waves overwashed dunes up to 4.5 m elevation and transported large amounts of pebble cobble and debris as much as 75 m across the backshore where dunes were less than 3 m elevation (CGVD28). Since 2003 the dune crest has retreated a maximum of 20.4 m and lowered by 1.4 m. The extensive low, wave overwash area along central Cherry Hill Beach has expanded 140 m eastward and waves cut two new channels through former trails through the dune. Sand is being swept from the ends of the beach and carried landward by wave overwash to infill the pond back of the central beach. The eastern beach has retreated nearly 10 m since 2003 and it was scoured down to a level similar to after Hurricane Juan. Since at least the late 1990s Cherry Hill beach has been experiencing rapid breakdown and landward retreat which Noel has continued.

Kejimikujik Seaside Adjunct, Queens County

A reconnaisance was made along Keji adjunct by D. Pouliot (2007) of Parks Canada on November 19, 2007. He did not find any significant changes to the physical beach system. The dunes were scarped and trees were undermined by waves along the western portion of the beach. Dune erosion was locally significant but within smaller areas than the western beach . Wind blown sand was accumulating along the east end of the upper beach but it may have been the product of higher winds after Noel. The abundance of seaweed and holdfasts was impressive as was other garbage and number of lobster traps carried ashore during Noel.

In a separate trip D. Mercer found evidence of a surge, possibly with a major wave setup component. North of the point on the western side of the main beach was a small lagoon / pond along the shore path. In that area the boardwalks were twisted or moved, some over 100 metres, with one or two small sections being flipped over.

Discussion

The landward extent of wave run-up and backshore flooding during Noel included some of the greatest since our storm observations were begun in the 1990s. Flooding and stronger wave run-up occurred at specific locations because of shore orientation and the longer duration of Noel. For example in Peggy's Cove and Queensland Beach specific buildings and infrastructure were damaged because of 1) the blockage of natural drainage routes which caused increased flooding, 2) damage to flood control structures which allowed increased water flow, and 3) movement of large rocks causing localized damage.

Many of the same impacts to low lying shore areas observed during previous storms reoccurred during Noel such as flooding, deposition of debris on roads and lawns, and damaged wharves, torn siding on houses and fallen trees. Less flooding of infrastructure occurred during Noel than Juan at the head of the bays, eg. Chezzetcook Inlet and head of Bedford Basin because maximum water levels were less than Juan. This was primarily because of timing. Water levels at the time of Noel were 40 to 50 cm less than the spring tides which had occurred a week earlier. If this event had occurred in the previous week, in all probability the intensity of coastal damage would have been comparable to Juan, and would have extended over much of the Atlantic Coast of Nova Scotia. The condition of infrastructure was also important, as many wharves and shore protection structures were rebuilt and reinforced after Hurricane Juan, resulting in less damage during Noel.

No official dollar values have been published for the cost of Noel. The worst damage to infrastructure was on the outer coast, in the vicinity of the Lahave River, at Peggy's Cove and localized impacts along St. Margarets Bay. Other places impacted included: Three Fathom Harbour Fishermans Reserve, Lawrencetown, Cow Bay, Metro Halifax, Prospect, Green Bay and West Berlin (Appendices 1 to 3).

Greatest impacts to natural beaches were at Cherry Hill, Crescent, Hirtles, Queensland Lawrencetown and Martinique which are all oriented toward the direction of largest waves (190 to 220º). Distance and elevation of landward wave run-up across beaches were similar to Hurricane Juan despite slightly lower sea levels. Highest levels were recorded at Lawrencetown Beach where wave run-up reached 6.3 m elevation at the top of the primary dune and the main debris line was slightly lower at 4.9 to 5.8 m. Wave run-up was also extreme across bedrock shores. For example at Peggy's Cove waves reached an estimated 12 m elevation. Elevations of floodlines (stillwater lines) surveyed were less than those measured after Hurricane Juan. During Noel floodlines reached ~2.3 m elevation on the shore road, at the Head Chezzetcook Inlet ; 1.9 m at Whyndenfog Lane, Lawrencetown Beach; ~2.2 m at salt marsh trail in Cole Harbour; and a maximum of 2.9 to 3.1 m at Hirtles Beach, Hartling Bay. Also, at the head of the bays and estuaries the force of the flood water was not as strong as during Juan. For example during Noel, skeet shells from the nearby rifle range littered but not washed over the salt marsh trail, houses landward and lower than shore road at the head of Chezzetcook Inlet were not impacted, and boardwalks rebuilt at Conrads and Hirtles Beaches remained intact, partly because they were made more sturdy after Juan.

Sand dunes occur at six of the eight beaches investigated. By October 2007 just prior to Noel, sand had accumulated along the upper beach, new foredunes existed and vegetation was spreading.

Where dunes had a more gradual seaward slope, waves from Noel ran up and over the dunes, flattening the grass but causing little scouring. Where new vegetation was growing across the upper beach and dune ramp, waves trimmed the grass but did not damage the roots. Many backshore washover flats received an influx of new sediment, grass cuttings and other flotsam which added to their long term rebuilding process. Best examples of this were observed at Conrads Beach and along parts of Martinique Beach, however severe scouring at weak parts of Martinique Beach were recorded.

The largest dune retreat was observed where boardwalks and other artificial structures, e.g. fences or buried debris, extended seaward of the dune and where the dunes had aggraded very quickly forming a high, steep seaward face. Waves breaking or running up against these obstacles or steep dune faces became turbulent and caused accelerated scouring.

The most severe dune erosion was at Crescent Beach, Lunenburg County where the dunes were cut back from 2.9 to 5.7 m since the last survey in 2003. Based on photos taken in October 2007 just before Noel the loss of dune was probably 2 m to 3 m more than what we surveyed because of seasonal sand buildup between surveys.

Dune height is another factor controlling wave impacts. Waves generally washed over dunes lower than 4 m elevation, and where the backshore was lower, seawater flowed over the dunes cutting channels across their backside. Where low dunes were fronted by pebble cobble beaches, the pebble cobble was transported and deposited 10s of metres across the dunes. At Conrads Beach waves during Noel removed sand from the upper beach exposing a pebble cobble substrate which was little altered. It was initially concluded that the coarse

sediment provided a natural built-in defense reducing further erosion, however it was more likely not eroded and moved landward because it was not exposed until near the end of the storm.

Where dunes were higher than 4 m and had even the slightest cliffed slope, waves cut them back and downward at their base leaving a larger cliffed profile. The largest retreat of high dunes was measured at Martinique Beach where waves cut them 3.4 m landward at line 7 (Fig. 31) and scoured its base by 1.2 m. Where a well defined sand ramp fringed these higher dunes waves merely ran up the dune slope causing little permanent damage .

The most severe cuts through the barrier beaches and dunes were at isolated places along Lawrencetown, Martinique and Cherry Hill beaches. Waves cut 5 to 10 m wide channels, as much as 2.1 m deep through narrow parts of the primary dune. At Lawrencetown Beach waves broke through a narrow neck of dune fronting a low dune slack or man-made excavation crater. The dune had been scoured and weakened by waves overwashing it during Hurricane Juan. During Noel, dune sand underlying the pebble cobble beach was exposed and easily scoured by breaking waves. At Martinique Beach a channel was cut 20 m through the dunes to the back estuary at line 5 (Fig. 28). This was one of the most narrow sections of the primary dune and also the site of a dune blowout initiated by human activities. Since the early 1980s the blowout has intermittently expanded eastward. Sand fences were set up across the blowout a number of times with good success in accumulating sand. However people continued to walk around the fences forming a low trail which waves flowed along during Noel. Once the water started flowing through the dune, it became more concentrated and it accelerated scouring of the breach.

The largest cut through a barrier beach was the 4 m deep channel cut 35 m along Hirtles Beach. An examination of barrier beach stratigraphy at the cut confirmed wave overwash had frequently occurred in the past, however local residents could not remember the barrier ever being cut before. There is no straight forward explanation for why the channel occurred at this location during Noel. The channel was cut through the barrier roughly half way across it which would likely be the weakest part and water was commonly observed flowing from the pond to the ocean beneath the beach near that location. It is postulated that the volume of water flowing into the pond by wave overwash from the sea during Noel raised the pond water level sufficiently to break through the barrier from the pond side. It is not known why it had not happened before. As of January 19, 2008 the channel had started to close and by late February, 2008 local residents reported water level in the pond had reached pre-Noel levels (T. Congdon, pers. comm. 2008). The low channel across the barrier beach was partially infilled with sediment.

Wide, high sand dunes, with a thick grass cover provided a more effective buffer for backshores against short term wave attack than armour rock. The grasses and increased elevation slowed water flow and allowed water seepage, thereby reducing scouring. Armour rock stops the waves but rock, debris and wave spray create hazards and cause damage to roads and other structures within the immediate backshore. Storms of several days duration can erode dunes 7 to 10 m landward whereas armour rock, of sufficient size, would provide a more solid defense. Artificial structures may require expensive

maintenance after storms. Dunes require sediment, vegetation growth and time to rebuild. It can take up to 10 years for the dunes to rebuild themselves after major storms.

At gravel barrier beaches the positions of the barrier crest (highest points) and lagoon shore were measured before and after Noel. Across low (≤ 4 m) beaches, e.g. Cow Bay, the crest migrated a maximum of 5.8 m landward and the lagoon shore migrated as much as 10 m whereas during Juan the crest was pushed nearly 24 m landward and the lagoon shore less than 5 m (Taylor et al. 2004). At the high (> 4 m) gravel beaches, e.g. Miseners -Long beach, landward crest migration was an average of 1.4 m and up 3.8 m where the crest was lowest prior to the storm.

High gravel barrier beaches, especially those without a tidal channel, are fronted by a sand apron. During large storms, waves scour down the sand and carry it farther offshore. Waves during Noel removed all sand down to the gravel substrate. At Miseners- Long Beach a wedge of sand 0.7 to 1.1 m thick was removed resulting in a loss in beach width of 13 m to 26 m near low tide. Where cobble existed just offshore, the waves flowed directly across them and did not scour downward, ie. Cow Bay Beach

Across the foreshore zone most sand beaches suffered a net loss of sediment at and above high tide level and either a slight net gain or larger loss across the lower foreshore. The difference in beach width before and after the storm was generally less than 6 m but in a few cases were as high as ± 9 m. Across the gravel beaches, swash ridges were already building near high tide level by the time of our surveys.

An aspect that does not receive much attention when large storms strike the coast is the impact of seaweed on beach dynamics. At all eight beaches investigated, seaweed was scoured from the seabed and began moving onshore as the storm waned, (Fig. 6b,22b,40b). In some cases the seaweed floated ashore still attached to cobble holdfasts (Fig. 48) It is not known what percentage of sediment re-supply to beaches comes from seaweed transport onshore, but it is a mechanism for transferring coarse clasts ashore from deeper water. Waves quickly push the seaweed upslope and shape it into swash ridges or beach cusps mixed with pebble cobble clasts. These ridges can restore barrier beach crest elevation faster than forming pebble cobble ridges, e.g. Cow Bay Beach. The seaweed tends to trap and collect clasts as they are transported upslope or tossed on top of the seaweed.

Figure 48. View of seaweed and cobble holdfasts carried onshore at the east end of Lawrencetown Beach after Post-tropical Storm Noel. It is a mechanism of transporting larger clasts onshore from offshore. Piles of seaweed accumulated alongshore also provided temporary protection for the beach against further wave attack (photo PB060423, R. Taylor).

A deposit of seaweed 0.6 m thick was very effective at dissipating wave energy striking the beach. For several days after Noel, the surface water consisted of a thick band of seaweed which was very difficult to walk through. The seaweed acted much like slush ice in winter, dissipating wave energy coming onshore. The net result was to provide a temporary defense against waves as part of the natural beach recovery process. Also, the longer period waves of Noel would have scoured the seabed at deeper depths, potentially increasing the source area of seaweed.

Why were the dunes of Crescent Beach, Lunenburg County more severely scoured and damaged than at Conrads and Martinique beaches?

It has been postulated for sometime that Crescent Beach is in a degraded state because it has been artificially restricted in its natural migration and growth by the presence of the highway. As sea level rises, the beach gets squeezed out and the lack of a wide high beach limits the supply of wind blown sand for dune building and the space for dune expansion.

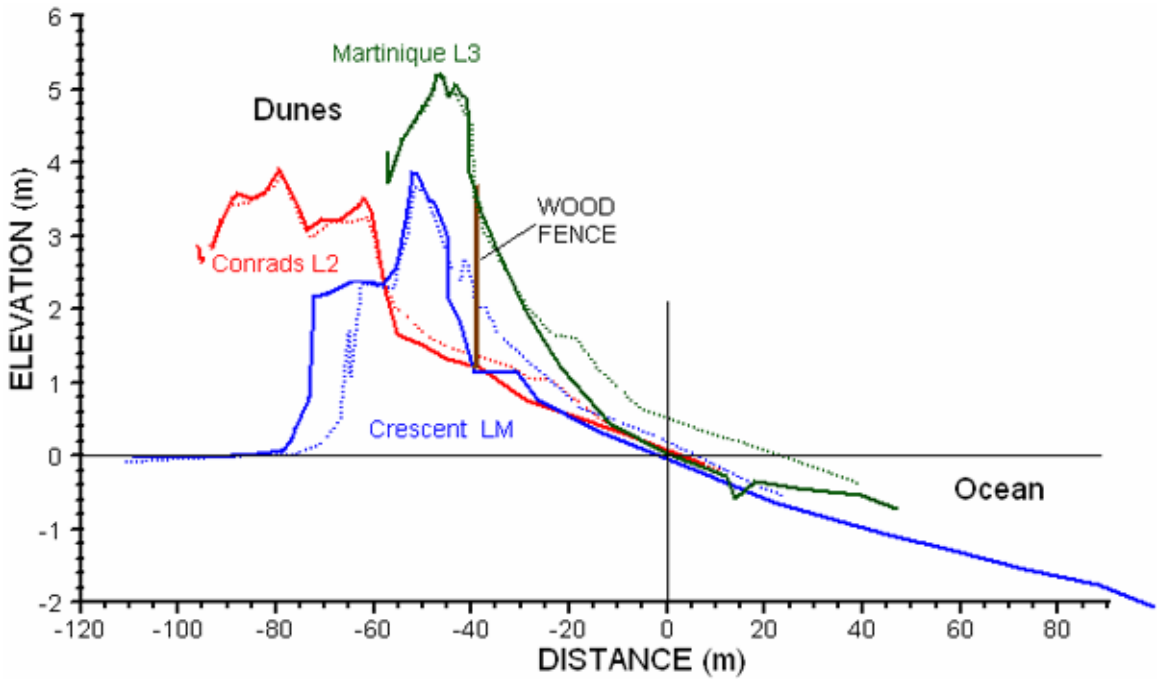


Figure 49. Cross shore profiles of sand dunes at Crescent, Conrads and Martinique beaches aligned where the beach slope intersects 0.0 m elevation in Nov. 2007. The zone of net beach erosion from two to three years ago (dash line) until after Noel (solid line) is shown for each beach. The position of the sand fence on Crescent Beach is also plotted.

All three beaches are sand dominated although Conrads Beach consists of more gravel than the other two. All three have a similar orientation to incoming waves. All three have a similar beach slope. Figure 49 provides a comparison of profiles across the three beaches, aligned using the 0.0 m (CGVD28) elevation intersect. For each beach a survey from 2-3 years ago was compared with the survey taken immediately after Noel. All three beaches experienced erosion across their upper beach and Crescent Beach suffered the largest dune erosion. Dunes at both Martinique and Conrads Beaches are wider than those at Crescent Beach. Dunes at Martinique Beach are much higher and the sand ramp is better developed which would promote wave run-up rather than scouring. The dunes at Conrads Beach are roughly the same height as those at Crescent Beach but they are farther landward and a foredune has developed farther seaward since the 1980s. Crescent Beach has the only physical structure of a massive wood fence. The largest loss of sand during Noel was adjacent to the fence.

It is concluded that Crescent Beach does not have the sand supply nor space to naturally expand its dunes, therefore the dunes are lower, smaller are located closer to wave attack and tend to have a cliffed face. During smaller storms when waves run-up to the fence, but do not break against it, the fence traps sand and debris. During large storms such as Noel and Hurricane Juan when waves break against the fence, it causes increased water

turbulence and scouring of the dunes. If true, why were dunes at Crescent Beach damaged so much more during Noel than Juan? The biggest difference between Juan and Noel was the longer duration of large waves during Noel. Also, the wave orientation was more from the SW during Noel and more east of south during Juan. In both storms the dunes had built seaward of the wooden fence before the storm. Waves during Noel had a longer time to attack and cut back the dunes and break apart the fence.

Summary

Post-tropical Storm Noel struck Atlantic Canada on November 3-4, 2007. Wave impacts were greatest along Atlantic coast of Nova Scotia. Impacts extended from Port Joli to just east of Clam Bay but were greatest east of Liverpool.

The area of gale to storm force southerly and southwesterly winds was at least an order of magnitude larger in Noel than Hurricane Juan in 2003, and extended along most of the Atlantic coast of Nova Scotia. Sustained wind speeds offshore peaked at 70 knots (130km/hr) during Noel and 82 knots (152km/hr) during Juan. The direction of waves was just west of south when their heights peaked and the duration of waves higher than 8 m was 6 hours.

Key parameters which differentiate Noel from previous tropical storms such as Hurricane Juan include: lower water level; less wind intensity, longer duration of high intensity waves; larger area of storm and greater wave setup of ocean, specific wave orientation; and larger extent of coastline impacted. Similarities with Juan include: timing, both occurred in the fall and in the night, Noel generated similar size waves and struck the same segment of the Atlantic coast of Nova Scotia.

If Noel had occurred in the previous week when spring tides were 40-50 cm higher, in all probability the intensity of coastal damage would have been comparable to Juan, and would have extended over much of the Atlantic Coast of Nova Scotia

The Atlantic coast of Nova Scotia has been retreating landward for thousands of years because of sea level rise. Storms such as Noel cause one small step in that natural process which varies in magnitude depending on the condition of specific shores. For the eight beaches investigated Noel maintained the rapid breakdown and landward migration of Cherry Hill and Cow Bay, left parts of Lawrencetown and Martinique more susceptible to rapid change, continued the slow migration of Hirtles and Miseners-Long beaches, and had less impact on Conrads Beach which is in a building phase. The backshore habitat at Hirtles Beach was dramatically transformed from freshwater to saltwater. At Crescent Beach, dune erosion from Noel triggered a management decision to further armour it with rock and constrain its natural movement.

At all beaches investigated, the seaward dune crest or storm ridge was lowered by 0.4 to 1.4 m and pushed landward by 5 to 8 m. Where water reached the lagoon, the shores were

extended as much as 10 m. Dunes were eroded back by 1 to 7 m and narrow channels up to 20 m long were cut through the dunes where water flow was concentrated.

Waves overwashed all shores less than 4.4 m elevation and water flooded up to a distance of 84 m across the backshore. Where backshores were higher, wave run-up extended to elevations of 6.3 m across vegetated sand dunes and possibly as high as 12 m across smooth bedrock shores. The minimal regional building guidelines in Halifax Regional Municipality are 20 m distance and 2.5 m above ordinary high tide level which is an elevation of 3.2 m (CGVD28). In select locations, the guideline for building setback has been increased to 60 m distance from ordinary high water. Given the elevations and distances that water reached on shore during Post -tropical Storm Noel, a further review of existing and proposed coastal building guidelines is warranted.

A number of large storms have been monitored since Hurricane Hortense in 1996. The same areas of highway are impacted by wave spray, and debris, especially roads armoured with large rock. It would be useful to post signs on these roads warning drivers to watch out for flying rocks, spray and floodwaters during storms.

Acknowledgements

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Appendix 1

Coastal Network:
Reports from coastal residents canvassed by telephone Sunday afternoon, Nov 4, 2007.

Saulnierville -Metegan, Digby County - Rene Belliveau reported no news of damage or significant shoreline changes but he had not been down to the shore. Rene reported everything was quiet there until the winds shifted to the SW when the system went by.

Crescent Beach Lockeport, Shelburne County - Joyce Young-reported beach fared well with some water over the road east of the Beach Centre including some debris and seaweed.

Liverpool-West Berlin Queens County - Jill Comolli- reported bridge knocked out, shed washed up onto road and foundation of new house flooded. Road at Ragged Harbour filled in by beach and water overwashed parts of dune at Beach Meadows -photos submitted at a later date showed impacts at Cherry Hill, Ragged Harbour and East and West Berlin .

Hirtle's Beach, Lunenburg County - Marilyn Congdon reported the boardwalk back of the dunes was uplifted into the pond to the west and the beach fronting the pond east of the parking lot was breached and the lake drained. She was not sure by how much but it is the first time she remembers this barrier beach has been breached.

Prospect, Halifax County - Nate, NS Climbing Club
I got a chance to check out the boulder shifting in Prospect last night. Wild! This recent hurricane packed a much bigger punch than hurricane Juan. Back Breaker start has no boulder beneath it (the name sake is still there unfortunately), Arm Bar has a flat landing, the arete to the right of Arm Bar has a big boulder under it, Sang du Dragon is even worse than before, and the most amazing change I saw was that the Fishing Girls boulder and the Evil Twin boulder are now spread apart a couple meters.
Has anyone seen Polly's or Dover? I can imagine those areas saw some major changes.
http://www.climbeasterncanada.com/viewtopic.php?f=4&t=4139

Cole Harbour Marsh Trail, Halifax County - Jim Tudor -the trail was all overwashed by water which carried the fine material to the landward side of trail-larger rocks remained - some scouring at the bridges but the trail was littered with gun casings from the skeet club which suggests the club was flooded and the water flowed more gently over the trail than in Hurricane Juan. Jim estimated maybe 1ft of water flowed over the trail. The 4th bridge was covered by cobbles -elevation at ends of bridge is 1.91-1.94 m.
Jim also heard that Rainbow Haven beach benefited from an influx of 3 feet of sand from the storm.

Lawrencetown Beach -East end (Wyndenfog Lane) - Betty Houghton sent photos from Sunday morning and reported flooding across the backshore as water came from the east end of the beach -not as bad as other major storms but still substantial. Water was also flowing down the channel along the west side of the Dominie's place. Mr. Houghton said water came in about 7am AST after the wind changed direction.
-West end -Don Forbes reported boardwalk damage by armour stone and debris littered across the highway and an abandoned car in the dune. There was extensive trimming of the dune face at the west end of Lawrencetown Beach, gravel deposited on top of the dunes and overwash into the parking lots west and east of the canteen through a couple of low areas of the dune. There was enough sediment on the roads at Lawrencetown and Fishermen's Reserve to require heavy equipment to clear the road.

Three Fathom Harbour to Grand Desert, Halifax County -Don Forbes reported highway flooded and washed over especially from the west -may have been some splashing coming over rocks at the Fishermans Preserve as well. The barrier beach crest at Seaforth was truncated by a washover channel cut through the west side of the 'Gaetz Cove' barrier and associated washover lobe of cobble gravel deposited across the private road there. Where wave overtopping occurred, impacts ranged from marsh grass debris on the road at West Chezzetcook, floated trees almost blocking the road at Grand Desert to pavement and shoulder damage at Fishermen's Reserve and Lawrencetown.

Miseners Long Beach, Halifax County -Margy Wade said there was a fair bit of water flowing over the dunes at the west end by the pond bathing beach. The old vehicle tracks along the backshore were infilled with pebble cobble. She reported it did not seem as severe as Hurricane Juan. Don Forbes confirmed these changes.

Martinique Beach, Halifax County -Gail Geddes reported many boardwalks damaged and cobble washed up onto the road and water ponded in the low areas just east of her office. Debris washed into parking lot 4 and dune cuts and boardwalk damage also severe at this location.

At 16:00 AST, Nov 4, 2007 Bob Taylor observed large surf inshore -waves reach nearly to base of dune east of L4 where dune grass was trimmed off during the storm. Boardwalks at most parking areas were damaged and debris was swept onto the lower dunes at the west end and 1.8-2 m high scarps are cut into the dunes. Along the eastern end of the beach toward the bedrock outcrop water had flowed east around the sand fences at line 5 and breached the barrier beach cutting a 5.7 m wide, 1.2m deep channel through the barrier beach. Pulses of water were intermittently flowing into the breach at 16:40 AST. Pieces of boardwalk were found all along the eastern end of the beach and swept up into the dune cuts. Waves washed over the dune crest at a number of places east of the rock outcrop including the 1998 breach. Water flowed to the lagoon shore and scoured a narrow channel through the lagoon beach but little damage to the newly formed dunes

Owls Head Beach, Halifax Co. -Neil Burgess reported that the beach was lowered and pushed landward but nothing serious occurred.

Louisbourg Historical Site, Cape Breton County -Fortress watch keepers reported big waves striking the outer coast but it was fairly quiet at the fortress end of Louisbourg Harbour wind was from offshore but he is not sure of outer coast where big waves

Highlands National Park-Cheticamp, Inverness County - Gerald Bourgeous reported no flooding in Cheticamp but high winds. There was a small amount of debris on road but no major damage -rivers were high but subsiding by the morning of Nov 5. He had heard Ingonish shore had more tree damage especially by the Keltic Lodge. Park Warden at Ingonish could not be reached for comment.

Appendix 2

Field observations of impacts to coastal infrastructure from post-tropical storm Noel in comparison to impacts after Hurricane Juan in October 2003

Areas visited (from East to West) notes by D. Mercer, Environment Canada

Area's visited during Juan are **bold-faced**, and actual sand beaches are *italicised*. Areas underlined were visited on Monday, November 5, while others were visited on the weekend of November 10-12, 2007.

- **East Chezzetcook**
  - The shore road had been flooded, but no tide lines were evident on the lawns or buildings. This was weaker than Juan.
- ***Fisherman's Reserve***
  - The causeway to the island was flooded in three sections.
  - In the dock area of the island, debris was on the road and the docks
- ***Three Fathom Harbour***
  - A witness reported water flowing at least 60 cm over the road. The debris line on his lawn was greater than 60 cm above the road.
  - Waves broke near the harbour mouth, and there was little wave activity near the shore.
  - A walking bridge on the west side of the harbour is reported to have had water up to 3-6 feet below the deck.
- ***Lawrencetown Beach***- see main report for details

- ***Dartmouth-Eastern Passage Shore*** - R. Taylor
  - Downtown Dartmouth there was buckling at the north end of the yacht club docks-less damage than in Juan, siding blown off the east side of a house on Portland Street near Moffats Drug Store and pieces of the roof from the Nova Scotia Hospital, Pleasant Street were found on the lawn.
  - In Eastern Passage a wave- exposed portion of the road (sharp bed just south of Fisherman's Cove) leading to Hartlen Point was damaged and covered by rocks -similar in Juan. The guard rail was scoured out and bent inward and pebble and cobble debris was deposited across the road against the front door of a residence.

- **Bedford Yacht Club and Vicinity**
  - Flooding was easily visible from the Lion's Playground to east of the Sackville River mouth
  - The playground had multiple debris lines and some logs, etc
  - There were planks and wooden panels in the yacht club

    - Debris lines and some damage to wharves was evident near and east of the club
    - A yawl named Reverie was wedged against the east bank of the Sackville River mouth. (several sailboats were floated on shore and yacht club severely damaged in Juan).
    - Overall damage was mostly surge, with 2 metres or less of wave activity, and was probably less than Juan's damage
- Sanford Fleming Park
    - Debris line just above the south jetty near the parking lot
- **Herring Cove**
    - Damage was less than Juan, probably due to the wave direction and the lesser surge
    - The south concrete dock had kelp on it, but there was no significant movement of the barrier rocks.
    - After Juan I had to clamber over rocks to reach the dock.
- **Ketch Harbour**
    - Again, the wave direction and surge was probably important in explaining the difference with Juan
    - During Juan, the main dock had its deck heavily damaged. This time, the dock was undamaged, but there was a debris line above the dock.
- **Sambro**
    - Reports of two private wharves destroyed.
    - Strong wave activity, but the direction kept the harbours more sheltered than Juan
    - Similar or larger surge reported, with a large undertow and a description consistent with short period seiching.
    - Coast Guard reported 11 buoys out of place, and they were starting a survey of their area of responsibility. One buoy was 1.6 km out of place.
    - Their anemometer peaked at 92 knots (instantaneous, not a gust), and the kept their anemometer this time!
- **Pennant**
    - Reports of two docks damaged/destroyed. I saw one, and the other may have been cleaned up or fixed.
    - Flooding on roads
- **Prospect**
    - Witnesses reported similar waves and surge as Juan, longer duration effects, but there was less to damage. Structures had been either repaired and strengthened, or not replaced at all.
    - Damage observed
        - Two private wharves destroyed
        - Rocks covering the front lawn of a house
        - A shed was displaced onto a neighbor's lawn, repeating its performance during Juan. But it went further this time.
        - Significant debris and erosion, especially on the Indian Head trail
        - A lot of kelp on the shore

    - A point on the Indian Head trail is known for waves breaking during good seas, with spray occasionally reaching the height of the point. In the case of Noel, waves scoured the barrens turf over 20 metres above sea level, also overturning large rocks.
- **Peggy's Cove** -see details in Appendix 3
- **Indian Harbour**
    - High water levels flooded low roads on the coast, and there was minor damage to some structures.
    - Paddy's Head Road connects the mainland to two islands via causeways. The north causeway was damaged by waves and surge from the south, and the guard rail was driven across the road blocking the islands from the mainland for a significant period. The causeway was not breached, and has been fixed, except for the guard rail and some detail work.
- ***Cleveland Beach***
    - This was hit by Juan, and the damage from Noel was a no greater. The beach lost more than half of its sand, there was erosion along the road comparable to Juan, which has been fixed
- ***Queensland Beach***
    - The damage here was considered by locals to be worse than Juan.
    - To me it seemed that the extra damage and perceived damage was due to the longer duration of waves and the effect on the park road and Route 3 nearby, as well as the fact that the stream on the west side of the beach under the bridge had been blocked, effectively flooding the parking lot.
    - Having said this, Queensland beach is mostly a boulder field, the parking lot is the same, and the road, especially along the eastern end near Route 3, is a wreck. It is badly heaved, and heavily eroded on the ocean side.
    - The parking lot is no longer flooded, since the stream was cleared. There was heavy gullying along the guard rail between the road and the parking lot. To me this was similar to Juan. The condition of the beach was also similar.
    - The other problem making it worse was that the erosion extended onto Route 3, blocking traffic for up to 15 minutes at a time.
    - Of those beaches I visited, this one is the most prone to damage from waves taking the right trajectory. It is the narrowest, the shallowest, has no plant life to stabilise the beach, and the bathymetry allows waves to break reasonably close to the shore.
- **Fox Point**
    - Erosion and repairs on and around the bridge. Debris inland
- **Mill Cove**
    - This was heavily eroded and there was some structural damage during Juan.
    - This year there were signs of repair work, and kelp on the platform of the beach park, but the damage looked to be significantly less.
    - I would guess that the wave trajectories were a bit too southerly, and the storm surge was a less than Juan.

- ***Bayswater Beach***
    - the beach is shallow, and the bathymetry offshore is shallow. Waves break further offshore and nearshore waves are not large.
    - on the east end of the beach the backshore rises a metre to a field of shore grasses, and the parking lot or road. The grass edge was heavily eroded, and water extended over the grass, but little reached the road.
    - at the western end of the beach sand mixed with rocks extends up to the road. Water went over the road and the debris line extended to the parking lot of the Swissair 111 Memorial.
- **Blandford**
    - There was some flooding over the lowest road sections, with a little debris on the land side.
- ***East River***
    - The shore road had waves over it, pushing rocks inland, and there was a debris line almost to a house.
    - There is significant erosion, and there has been some repair work.
- **Graves Island Provincial Park**
    - There is kelp and debris over the causeway to the island.
    - On the south side of the island there are debris lines above the road level on the grass.
    - There is no sign of significant wave damage.
- **Chester**
    - There is debris on the yacht club wharf.
    - In back harbour a jetty looks damaged. Many look extremely sturdy, and I wonder how many are post-Juan
    - Near the Tancook Ferry is a damaged wharf. Steve Hatt has a picture from just after it was damaged.
- Gold River
    - Flooding just up to the road
- Blue Rocks (observations near and after dark)
    - Flooding and wave activity across the road onto some front lawns. Significant small to medium rocks. Significant erosion.
    - Also, flooding and debris, as well as road erosion just north of Blue Rocks
- *Hirtle's Beach*-see main report for details

- Dublin Shore
    - Bells Cove Road was heaved and eroded, and covered with shale in parts, and with kelp and debris in other parts.
    - The large government wharf was perceptibly twisted along two different axes, partially from Juan, but substantially from Noel.
    - The road to the government wharf is lined with fishing sheds. Every second or third one is destroyed.
    - There was heavy erosion (6 feet deep and back 6-10 feet) back to the wharf road and the main road.
    - A wharf was destroyed, and the remnants have ended up across the harbour in the eroded section.

- *Crescent Beach*- see main report for details
- *Risser's Beach*
    - Still completely sand, but maybe a bit less of it.
    - Erosion, with tree roots exposed all along the shore
    - The debris line at the north gate extends to the entrance building.
    - Several trees are down as a result of strong winds

Appendix 3

Peggy's Cove: Damages from Post-tropical Storm Noel compared with Hurricane Juan

Background

Peggy's Cove is an area famous for the way that waves break along the shore near the lighthouse. This is partially due to the steep drop-off along the south-facing area of shoreline near the light. Long period waves can move very near the shore before they break, and they often break more than twice the height of the incoming waves. This attraction usually claims the lives of one or more naïve tourists each year, when they move too far seaward on the rocks.

However, most of the village and the harbour are well protected from the waves, and are seldom impacted. The worst damage in recent history prior to Noel was Hurricane Juan (http://www.atl.ec.gc.ca/weather/hurricane/juan/peggys_cove_e.html) on September 28-29, 2003. Damage was significant, including massive boulders being moved and broken, the government wharf was damaged, and flooding occurred well north of the usual areas. In fact, east of the harbour, at the top of a rise in a valley, is a breakwater constructed in 1915. This was built to prevent water that flooded the southern valleys due to major winter storms from coming into the village along the valley. Hurricane Juan was one of the few events over the last hundred years that caused flooding of the village from this valley. The breakwater was overtopped by water by as much as two metres, yet survived Juan in good condition.

Shore damage from Noel compared with Juan is discussed. There were many similarities, and a few important differences between the two events, with significant and interesting implications.

- Noel moved north to north-northeast and passed near Yarmouth before dawn of November 4. Juan was moved almost directly north, and made landfall near Prospect, about 20 km west of Halifax.
- The area of gale to storm force southerly and southwesterly winds was at least an order of magnitude larger in Noel than Juan, and extended along most of the Atlantic coast of Nova Scotia. Sustained wind speeds offshore peaked at 70 knots during Noel and 82 knots during Juan. During Juan, the area of very strong winds was more localized, with the highest winds extending for about 100 km. east of the storm
- The larger area of strong winds during Noel produced waves at least as intense as for Juan, and covering a much larger area of the coast. Waves in excess of 8 metres impacted most of Atlantic Nova Scotia, while peak waves well in excess of 10 metres hit the central part of the Atlantic coast. For Juan, the area of waves in

excess of 8 metres extended from just west of Lunenburg to less than 100 km east of Halifax.

- The direction of the waves from Noel were just west of south (190-220 degrees) when their heights peaked, and the duration of waves higher than 8 metres was near 6 hours. For Juan, the wave direction for the highest waves was just east of south (160 degrees true) and the duration of waves above 8 metres was, at most, a couple of hours.

The duration and the directionality of the waves were the most significant differences between the two storms causing the shore damage.

Storm Damage at Peggy's Cove

The same areas were affected in both storms however the key differences were in the extent of damage, particularly along (1) lighthouse and southern rock ridge (2) the south gully (3) the restaurant facilities and eastern rock ridge and (4) the northern valley and village.

General Comments

- Noel was described as "the worst weather event" in living memory.
- Wave activity was described as similar to Juan, with greater duration and greater surge. However the surge description is not classic surge nor set-up, and is at least partially due to a flow of water from a valley to the east, which will be described later.

Lighthouse and southern rock ridge

- A south-facing window in the lighthouse was broken, flooding the post office inside. Power was lost when the underground lines were cut, and the paving stones of the path tossed like a bunch of playing cards.
- Movement of rocks by the waves was impressive. Many rocks moved up the south face of the ridge (see figure 3-2), others moved down the north face into the south gully, and at least one rock moved up the other side of the valley on to the eastern ridge (see figure 3-3).
- The largest rock moved was roughly 6 metres by 5 metres by 2 metres, with an estimated mass of 150 tonnes. It moved over 15 metres east to west and now lies southwest of the lighthouse (see figure 3-1).
- In this area there was significantly more damage from Noel than Juan.

Figure 3-1: The top image shows the footprint of the original location of the rock, labeled by A, with people for scale. The lower image shows the rock about 15 metres to the left of its origin. The rock is estimated to be 150 tonnes.

Figure 3-2:. The rock on the right of the person is flipped, the one on the left has been broken on the left side. The location is 4 metres above sea level, and the person is 1.65 metres (5ft, 5in) tall.

- **South gully**
  - The south gully is the low area between the restaurant/parking lot and the southern rock ridge (see aerial photograph). It slopes eastward into valleys which are routinely fill and drained of water by the tides.
  - South gully was severely scoured in places, trails were destroyed, and there was extensive erosion below the southern and southeastern sections of the parking lot. A large number of rocks have moved into the eastern part of the gully and broken.
  - The damage in this area was greater from Noel than from Juan.

Figure 3-3: This rock was broken and swept upslope from the south valley to about 8 metres above sea level.

- **Restaurant, parking lot, and eastern rock ridge**
  - The sewage treatment plant near the restaurant had its southern wall destroyed (as in Juan). Rocks and boulders also moved onto the parking lot which was eroded on its south and east sides (figure 3-4).
  - The eastern ridge extends eastward from the northeast corner of the parking lot, and is the northern edge of the south gully. It is about 10-12 metres above sea level. There is evidence of water flow and probably wave activity across the ridge as far west as the parking lot. Sods have been flipped back to the north, there are some areas scoured, and there is a new boulder on the top of the ridge. There were also signs of water flow down the north side of the ridge into the northern valley, east and west of the breakwater.

Figure 3-4: (Top) Erosion around east side of restaurant parking lot. (Bottom) All the large rocks shown were moved, some on top of paths.

- **Northern valley,**
    - There is a stone breakwater/dam at the highest point of a valley (see figure 3-5). which drains west into the harbour and east into the ocean. The breakwater was designed to protect the inner village from flooding during major storms. It has been there since 1915, and has never been damaged in living memory.
    - The breakwater was breached during Noel (Figure 3-5). After hours of steady pounding, it broke at about 3 am. A continuous flow of water up to 2 feet deep flowed over the harbour road.
    - Damage:
        - A barn moved by Juan was moved again
        - Water flowed past both sides of a yellow house, breaking shingles up to 4 feet above the lawn (again).
        - The driveway is now in the harbour (again)
        - A blue house was surrounded by water and evacuated (again)
        - A gift shop named Beale's Bailiwick had water running through its foundation, shifting it and creating a large ditch.(again)
        - The harbour road was eroded on both sides, and blocked passage between the south side and the rest of the village during the storm (again)
        - A lot of rock, dirt and debris is now in the harbour, adding to the amount from Juan
        - Some wharves were shifted. The main wharf was replaced after Juan, was much stronger and was undamaged

Figure 3-5: (Top) Breakwater (arrow) after Juan, with no significant damage. (Bottom) After Noel, with about half of it totally destroyed. The breakwater was built over 100 metres from the ocean and has remained undamaged for 92 years.

Waves and Storm Surge

Waves produced from Noel were more significant than during Juan, mainly because of the much longer duration, and longer wavelength. For a given wave height, longer waves tend to move more rapidly towards the shore, transport more water onshore when they break, and often increase the wave set-up which in turn increases the total storm surge. Also, waves with a longer period and wavelength break higher against these rocky shores.

Storm surge for this event was less than Juan, mainly because the spring tides had occurred one week before Noel. Maximum astronomical tide levels were on the order of 40-50 cm less than the spring tides along most of the coast. Wave set-up increased the water level, but it was still about 50 cm less than maximum level during Hurricane Juan.
It is important to note that if Post-tropical storm Noel had occurred one week earlier, it is probable that total water levels from Noel would have been comparable to Hurricane Juan. This, combined with the exceptionally high waves impacting the shoreline, would have extended coastal damage along most of the Atlantic coastline of Nova Scotia.

Summary

A large extra-tropical storm, albeit of tropical origins, inflicted damage to sections of the coastline exceeding that of a Category 2 hurricane that hit the same area 4 years earlier. The main driving force behind the damage was an extremely strong wind field covering a very large area, thus allowing waves to grow close to their full potential. Also the motion of the storm helped this development, effectively keeping the area of strongest winds directly over the fastest growing waves, which were moving northward with the storm. The large area of strong winds more than compensated for the fact that they were weaker than during Hurricane Juan. If the same storm had occurred a week earlier, damage along the coast by Noel would probably have been significantly greater in area, and possibly in intensity.

Related links

Storm chaser images and movies after the height of the storm, at Peggy's Cove and nearby

- George Kouronis report
- http://www.stormchaser.ca/Noel/Noel.html

- Mike Theiss report
- http://www.ultimatechase.com/Hurricane_Video.htm.

- Animated gif of a wave breaking across the restaurant parking lot
- http://www.ultimatechase.com/Chase_Accounts/Images/Hurricane_Noel/BigWave_Animation.gif

Canadian Hurricane Centre report on Hurricane Juan
http://www.atl.ec.gc.ca/weather/hurricane/juan/

Canadian Hurricane Centre report on Peggy's Cove
http://www.atl.ec.gc.ca/weather/hurricane/juan/peggys_cove_e.html